SCOPING RD&D PRIORITIES FOR A LOW CARBON FUTURE,

For the Carbon Trust

by

Imperial College

Centre for Energy Policy and Technology

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THE CARBON TRUST

The Carbon Trust is an independent, not for profit, company investing public and private finance in low-carbon technology and innovation with three objectives:

- To ensure that business and the public sector meets ongoing targets for carbon dioxide emissions
- To improve the competitiveness of UK industry through resource efficiency
- To support the development of a UK industry that capitalises on the innovation and commercial value of low-carbon technologies

The Carbon Trust was created in April 2001.

For more information on the Carbon Trust, please visit the website at www.thecarbontrust.co.uk

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EXECUTIVE SUMMARY

This report is a 'scoping' study intended to assist the Carbon Trust to plan and develop a research, development and demonstration (RD&D) programme in low carbon technologies. The study is based on both on our own analysis at the Centre for Energy Policy and Technology at Imperial College, and a series of informative and influential 'stakeholder interviews' with people in industry, finance, the research community, and government and non-government organizations. The report addresses:

A Low Carbon Economy. A transition to low carbon energy forms and use is seen to be technologically feasible, and unlikely to disrupt economic growth and diminish the UK's economic prospects. With innovation, economic prospects could be improved, and a low carbon UK economy would be far more prosperous than it is today. Energy would be abundant, but more efficiently produced and used, with a greater reliance on renewables as an energy source and hydrogen as an energy carrying and storage medium. The world can aspire to greater prosperity on a broad basis, and to the achievement of economic development, in a low carbon future. [Chapter 2.]

Scenarios and Pathways to a Low Carbon Future. A large number of studies have consistently shown that the key to moving toward a low carbon future lies in technical progress—specifically in the development and use of the low carbon technologies and practices. Hence the need for policies to support innovation directly. [Chapter 3.]

Thematic Priorities for RD&D. The strategic impact and deliverability of a range of technological options are assessed, together with social and economic research needed to assist their market development:

- ***Energy efficiency improvements in buildings***. Energy use in buildings accounts for over one-third of energy use. Areas where RD&D can foster further improvements include heating, cooling and energy management systems; building envelope and architectural improvements (the latter including passive and active solar building designs); and decentralised forms of combined heat and power.
- ***Energy efficiency improvements in industry***: Further potential for improvements in processes, heating, lighting and motive power.
- ***Transport efficiency improvements***: Major efficiency improvements and emissions reductions are feasible through fuel cell and hybrid (petrol- and diesel-electric) vehicles. Transport and congestion management policies are also central.
- ***Renewable energy***: There is a wide range of renewable technologies that could contribute to a low-carbon future: photovoltaics; biomass (from crops and wastes); onshore, coastal and offshore wind; energy from tidal streams and waves; hybrid wind-wave or wind-tidal stream devices.
- ***Energy storage systems***: for stationary applications and transport. A central area for research, required for the resolution of the 'intermittency problem' of renewable energy.
- ***Hydrogen production, storage and use***: Developments here would provide a carbon-free fuel and a means of storing energy generated from renewable sources.

- ***Fuel cells for the decentralised supply of electricity and combined heat and power:*** these promise an efficient means of utilising energy from natural gas and/or hydrogen.
- ***Efficiency improvements in electricity supplies from 'clean' fossil fuels***: these include coal gasification technologies, the use of coal-bed methane for electricity generation, and the supply of gaseous fuels for fuel cells and micro-turbines for decentralised sources of CHP. Coal gasification technologies are also potentially carbon free methods of producing hydrogen for power generation and transport *if* coupled with:
- ***Carbon sequestration***: including geological storage of carbon dioxide.
- ***The social and economic aspects of a transition to a low carbon future.*** Social and economic change will have an appreciable influence over technology development and use.

Some of these technologies, including energy efficiency, some renewable energy technologies (onshore and coastal wind, and biomass) and carbon sequestration require support to continue delivering incremental improvements in emissions reductions. However, it is vital that the Trust should also support technologies with good long-term prospects. The 'big impact' items in the long-term, which together are capable of transforming energy systems to a low carbon future, are solar and offshore renewable energy resources, new energy storage systems, hydrogen production, fuel cells and distributed generation. [Chapter 4.]

The Policy Context. UK policies on climate change and technology development continue to evolve (and are under further review at the present), and will greatly affect the deployment of new technologies and practices as they are developed. The Trust needs to be a participant in this policy-making process.

At the international level there are fault-lines between the US and the rest of OECD, and between the developing countries and the OECD. There is also a conspicuous gap—there is no international initiative to develop technologies of great long-term importance, which may hold the key to future international agreements on climate change. There is a leadership role for the Trust and the government here. [Chapter 5.]

Markets for the New Technologies. There are huge market opportunities for low carbon technologies and practices, but there are also social, economic and institutional barriers to their development and use. Policy options are available to foster market development. [Chapter 6.]

Recommendations to the Trust:

- Establish thematic priorities for RD&D on the above lines;
- Develop a broad portfolio of projects that would be well-balanced between medium term and long-term goals;
- Support research on social and economic issues connected with the transition to a low carbon economy; and
- Take a pro-active role in the development of policies at the national and international levels. [Chapter 7.]

1 INTRODUCTION

The Carbon Trust, which comes into operation in April 2001, aims to be a catalyst for change towards a low carbon economy in the UK. It will play two parallel and complementary roles: *firstly*, to help deliver major reductions in CO_2 and other greenhouse gas emissions over the next 50 years, and *secondly*, to help UK business to capitalise on the commercial benefits that innovations in low carbon technology can bring. This study was commissioned to "help the Carbon Trust to plan and develop a research, development and demonstration (RD&D) programme by ascertaining the RD&D needs and opportunities associated with moving UK business towards a low carbon economy".

This report aims to be both broad and forward-looking in identifying the technological, social and economic issues associated with RD&D needs and opportunities. It has been written by a team from Imperial College Centre for Energy Policy and Technology (ICCEPT) but it aims to reflect a wider consensus of views. In addition to critical reviewing of academic, commercial and policy literature, further ideas were gathered through a series of semi-structured interviews with key stakeholders in the business, research and policy communities. We benefited greatly from these interviews and, though views were wide-ranging and sometimes diverged, there were many views commonly held, which are reflected in the report.

The report has five main Chapters:

Chapter 2 scopes and defines what is meant by a 'low carbon economy'. Chapter 3 reviews a range of scenarios and pathways toward a low carbon future, in the UK and in a global context.

Chapter 4 is the main body of the report. Low carbon technologies and practices are reviewed and assessed, and there is a discussion of the relevance of social and economic research on technology choice, development, deployment and the policy environment. This aims to help the Trust identify thematic priorities for RD&D. The Chapter concludes by proposing ground rules for building a RD&D portfolio.

Chapter 5 examines the influence of UK and international energy and environmental policies on the delivery of the Trust's RD&D programme. Chapter 6 provides an assessment of social and economic opportunities and barriers to the development and take up of low carbon technologies and practices.

The report concludes with a set of recommendations as to how the Carbon Trust might take forward its RD&D programme.

The outcomes of the stakeholder interviews are summarised in an annex to be issued separately, along with annexes on our working notes, which provide more detailed assessments of the technologies discussed.

By agreement with the DETR, who commissioned the study, nuclear power is not reviewed below.

2 FEATURES OF A LOW CARBON ECONOMY

2.1 Towards a Low Carbon Future

The term 'low carbon economy' is taken to mean an economy whose energy demands are met with greatly reduced emissions of greenhouse gases to the atmosphere relative to today's levels. The report focuses on technologies and practices which reduce emissions of carbon dioxide, whilst considering other greenhouse gas emissions where relevant.

The United Nations Framework Convention on Climate Change (UNFCCC) commits nations to achieving 'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic (human-induced) interference with the climate system'. Under the Kyoto Protocol to the UNFCCC, the UK has agreed to reduce its greenhouse gas emissions by 12.5% from 1990 levels by the period 2008-2012. Beyond this, the UK government has a near-term goal of a 20% reduction in carbon dioxide emissions from 1990 levels by 2010. Looking at the longer term, the recent report of the Royal Commission on Environmental Pollution[1] commented that

> for "the UK an international agreement .. which prevented carbon dioxide concentrations in the atmosphere from exceeding 550 ppmv and achieved convergence (i.e. equal per capita emissions among countries world-wide) by 2050 could imply a reduction of 60% from current annual carbon dioxide emissions by 2050 and perhaps of 80% by 2100."

The policies and measures to meet and exceed the UK's Kyoto target and work towards the CO_2 reduction goal are given in the UK Climate Change Programme[2], published in November 2000. One of the measures in the Programme is the setting up of the Carbon Trust, which came into operation in April 2001.

The Carbon Trust's remit is to

- Work with business to develop a range of information, advice and auditing programmes on energy efficiency and low carbon technologies;
- Take forward the development of the Enhanced Capital Allowances scheme for approved energy efficiency and low carbon investments;
- Support research, development and demonstration projects;
- Contribute to the development of a long term strategy to move the UK towards a low carbon economy, ready to respond to the climate change challenges and opportunities which lie ahead beyond 2010.

There have been a large number of studies of the possible course of CO_2 emissions over the present century. The Special Report on Carbon Emission Scenarios[3] for the IPCC

[1] Royal Commission on Environmental Pollution, *Energy - The Changing Climate*, June 2000
[2] DETR, Climate Change: The UK Programme, November 2000
[3] IPCC, Special Report on Emissions Scenarios, 1998

reported on 150 peer-reviewed studies, with over 400 scenarios between them. (Those on the UK will be discussed in Chapter 3.) Estimates of emissions range by year 2100 range from zero to over ten times today's levels of 6 billion tons of carbon per year.

Despite this diversity of results, five conclusions can be drawn:

1. *A low (or even zero) carbon future for the world's economies, in the sense defined above, is technologically feasible*.
2. *The range of technological possibilities for reducing emissions in the near term is far more restricted than in the long-term.* This is not surprising, but it will be important for the Trust to keep in mind, since technologies that may make only a marginal contribution by 2010 are likely to loom large beyond then.
3. *Costs are also changing over time with innovation.* The 'learning-curves' for several important options are steep—for renewable energy, energy efficiency, and fuel-cells in particular. For this reason:
4. *The costs of a transition to a low carbon future are unlikely to be prohibitive.* At the global level, estimates range from a permanent increase of Gross World Product of up to 3% (an economic surprise cannot be ruled out) to a permanent loss of 4%, with a median estimate of a loss of less than 2%, or less than one year's economic growth. These estimates make no allowance for the benefits of mitigating climate change.
5. *Policies matter*—in the present case, on account of their influence on the directions of innovation, and on how quickly and in what ways markets are opened up to the new technologies and practices

Thus the possibilities being opened up by research and innovation mean that the world's energy demands could eventually be met with no CO_2 emissions into the atmosphere, even if the demands were to rise to three or four times today's levels. From both a technological and an economic perspective, there is no reason why the world cannot aspire to achieving economic prosperity on a broad basis, and to enjoying the benefits of energy use, in a low carbon future.

2.2 Low-Carbon Futures for the UK: (a) The Supply Side.

The report of the Royal Commission on the Environment is a good starting point. It presents four scenarios, in which the UK's energy demand in 2050 ranges from being the same as it was in 1998 (Scenario 1), down to 57% of this figure (Scenario 4). The 'mix' of energy supply technologies differs between the scenarios, on account of differences in the demands to be met, the low demand scenarios permitting the possibly more expensive options to be discarded. But in all four cases, the same set of technologies is called upon by 2050; it is most fully depicted by their Scenario 1, which is as follows:

- 50 large onshore wind farms
- 510 small onshore wind farms
- 180 large off-shore wind farms
- 15 million rooftop PVs
- 7,500 MW of wave power units

- 500 MW of tidal stream units
- A tidal barrage
- 4,500 small scale hydro
- 290-2900 CHP plants fuelled by energy crops (1-10 MW each)
- 53-1050 CHP plants fuelled by agricultural and forestry wastes (0.5-10 MW)
- 3-20 CHP plants fuelled by municipal solid waste (6068 MW)
- 55,000 MW of base load plants either nuclear power or fossil fuel with CO_2 recovery.
- 4,000 MW of fossil fuel plants to back up intermittent renewables.
- 4,800 MW of fossil fuel plant to meet peak demands.

Transport continues to depend on oil in all four scenarios.

This supply mix is, however, only one possibility. Its main limitation is that it is ‘more of the same’, an extrapolation of technologies already in use in the 1990s, with no allowance for new developments. There is, for example, no role for hydrogen, produced from either renewable energy or fossil fuels, for use in electricity generation or transport; no solution to the ‘intermittency problem’ of renewables; and no role for fuel cells for transport or for decentralised forms of heat and power. Innovations in offshore devices for the extraction of energy from tidal streams, waves, wind and solar energy supply are also ignored, as are developments in small-scale storage technologies. For transport, the technology remains the internal combustion engine with petrol or diesel being the primary fuel.

Figure 2.1 (see end of Chapter) summarises the options as depicted by Scenario 1 of the Commission’s Report. Figure 2.2 superimposes on it the wide range of emerging options for emissions reductions. The latter include:

- A wider range of possibilities for utilising renewable energy resources offshore.
- Hydrogen production from enhanced coal-bed methane production, renewable energy and natural gas.
- Fuel-cells and micro-turbines for decentralised forms of CHP, based on natural gas, hythane (a mix of natural gas and hydrogen) or hydrogen.
- Fuel cells for transport.
- A greater use of electricity in public and private transport.
- Small-scale, short-term local storage of renewable energy.
- Long-term (seasonal) storage of hydrogen.

All these could co-exist with the options of the Commission’s Report—or even supersede them. Aside from a solution to the storage problem, they have several further advantages: gains in efficiency, for example through the reduction of losses in electricity transmission and distribution, and the use of fuel cells for CHP and transport; and reduced requirement for future infrastructure investment associated with de-centralised forms of CHP. It will thus be important for the Trust to recognise the broad range of possibilities arising from research and innovation in industry and the research community. Chapter 4 discusses the options in more detail.

2.3 Low-Carbon Futures for the UK: (b) Energy Efficiency

Efficiency in energy use—as measured by the amount of energy required to provide specific quantities of heat, light and power to homes, commerce and industry—has increased steadily in the industrial economies for more than two centuries. The trend rate of growth is in the range 1 to 2% per year, sufficient to reduce demands (for specific purposes) by roughly two-to three-fold over a 50 year period, and three- to seven-fold over a century. The sources of efficiency improvement are almost too numerous to classify. For example, there were large gains arising from the substitution of gas and electricity for coal in homes and industry, of electricity for steam power in industry, and of oil for coal in transport; and from an extraordinarily wide range of innovations in energy using and energy saving products. Trends in energy conversion, especially electricity, showed similarly dramatic improvements. For example, the thermal efficiency of power stations increased by roughly five-fold in the first half of the last century and a further two-fold in the second half.

These trends were obscured by two factors. One was the rapid growth of demand for energy itself with the growth of incomes, industry, commerce and transport and of new energy-using devices. The other was that the efficiency gains, by reducing the costs of energy use, stimulated demand and new applications. However, as markets have matured, efficiency gains are beginning to exert a downward pressure on demand—though the evidence as to whether efficiency gains will offset the effects of income growth and price reductions is not yet conclusive.

Carbon emissions in the UK have been falling over the last 10 years, despite continuing economic growth, as a result of a combination of reductions in energy intensity, fuel switching in electricity generation from coal to gas, and increasing efficiency of nuclear power generation. Energy intensity has fallen because of:

- A shift in the balance of economic activity from industry to services;
- A shift from energy intensive to less energy intensive industrial production;
- Technical energy efficiency improvements in all sectors.

Energy efficiency improvements have been achieved through both 'good-housekeeping' measures (often aided by energy audits) and the uptake of more efficient end-use equipment and processes.

The scope for further improvements is far from exhausted, as illustrated in Figure 2.3. First, a number of innovations have still to be incorporated into the capital stock. For example:

- Industrial process: a wide range of ‘best practices’ in the use of heat and power.
- Industrial and commercial buildings: wall and ceiling insulation, improved efficiency in office equipment and lighting, and general innovations in architecture, building heating and air-conditioning services.

- The use of fuel cells or micro-turbines for decentralised forms of combined heat and power.
- Transport: lean-burn engines, and (especially) hybrid and fuel cell vehicles.

Large gains are also possible through reductions in urban congestion, urban development policies, reductions in travel made possible by the 'IT revolution', and changes in transport modes and lifestyles.

Further possibilities for efficiency gains—and also for the development of low carbon supply technologies—may arise from the mutual interests of the transport and energy sectors in the development of particular technologies. The electrical generating potential of the fuel cell vehicles expected to be on the road in the future (estimates suggest that the aggregate kW capacity of vehicle engines is some five times the installed stationary generating capacity on the grid) could be harnessed and integrated with the grid and with a variety of other energy sources and carriers, as shown in Figure 2.4.

Several studies have assessed the effects on carbon emissions of a wider uptake of energy efficient options for each energy-consuming sector. They suggest that further reductions of between 15 and 30% are achievable at relatively low cost in the next 10-20 years. As noted, the Royal Commission on Environmental Pollution considered four scenarios in which UK energy demands ranged from being 0% to 47% *lower* than 1990 levels. These are within historical norms and within the bounds of technological possibilities.

The main uncertainty is whether the effects of income growth will offset energy efficiency gains. The average UK per capita income would rise more than three-fold from £15,000 today to £50,000 in the next fifty years if the current—two-century long—rate of economic growth were to continue, and the Gross National Product from £850 billion to £3,000 billion. It would be misleading to claim that we know what the effects of such growth on people's demands for leisure, material goods, services and travel and thus for energy will be. What can be said is that:

- The future 'low carbon' economy will be more efficient in its use of energy than it is today, because the scope for improvements remains appreciable.
- Some of the efficiency gains will occur through innovations in industry itself, in transport, and in the energy appliance markets.
- The importance of policies to encourage efficiency improvements is increased, not diminished, by the possibility of income growth adding to people's energy demands. As part of this policy:
- A significant RD&D effort will be required, as has been the case historically.

Chapter 4 of the report discusses possibilities of interest to the Trust.

2.4 Costs and Economic Impact

A transition to low carbon energy forms is unlikely to diminish the UK's economic prospects. With innovation, economic prospects may in fact be improved. The same energy services would be available as are available today, but with the main carriers being gas (hydrogen) and electricity, at costs not far removed from those today.

The estimated range of the costs of such a transition is wide, but even if we take the upper end of the range, the negative impact on economic growth is likely to be small. As noted above economic studies have estimated that the economic effects of a transition range from a permanent increase of World Product of up to 3% to a permanent loss of 4%. In the former case the world would be better off economically, in the latter, 1-2 years of economic growth would be lost over the century. This implies that the long-term growth rates would change by around ± 0.1 percent per year. As one reviewer aptly remarked of the high cost case: "it is hardly Armageddon, is it?"

Further studies are still needed to assess the effects on the UK; what can be said at present is that, in the light of the emerging technologies discussed in Chapter 4 below, the effects on the UK's growth are likely to be similarly small, and could be positive or negative. Table 2.1 provides an overall assessment of what incomes, emissions and expenditures on energy might look like in 50 years or so, on the assumption of continued economic growth in the economy:

Table 2-1 Economic Aspects of a UK Low Carbon Economy

	Present[a/]	c2050
Per Capita Income, £	15,000	50,000
GDP, £ billion	850	3,000
Carbon Emissions, million tonnes	150	60[b]
Final expenditures on Energy:		
• Total, £billion (including taxes)	≈70	70-150[c]
• Percent of GDP (and of per capita income)	7.5	1.5-3[c]

Sources and notes:
a/ The figures for the Present are trended up from the Digest of UK Energy Statistics of 1997, and will be updated shortly.
b/ Assumes 60 percent reduction, based on the report of the Royal Commission on Environmental Pollution.
c/ Primary energy consumption was 230 million tonnes of oil equivalent (mtoe) in 1998 (BP Statistical Review), as compared with 212, 206 and 220 mtoe in 1970, 1980 and 1990 respectively. Growth is slow around 0.5 to <1.0 percent per year. The lower estimate assumes no growth of energy demand and no increase in the final real price of energy. The higher figure assumes 0.5% growth per year and a 50% increase in the real price of energy.

The current costs of low carbon technologies are often high; however, there is much potential for cost reduction, for example through

a) Continued innovation in—and scale economies in the manufacture of—renewable energy technologies. Costs have declined historically by 20-30 percent for each doubling of the cumulative volume of production;

b) Reductions in electricity losses and capital expenditures on transmission and distribution through distributed generation;

c) Reductions in the capital costs of generation through developments in fuel cells or micro-turbines;

d) The reduced infrastructure costs and the gains in energy efficiency achievable through decentralised generation and combined heat and power (CHP);

e) The greater energy efficiency of the fuel cell and hybrid engines for transport relative to the internal combustion engine;

f) Innovations on the demand side, which have been major sources of both energy savings and cost savings (consumers' surplus) historically;

g) Changes in transport modes, congestion management and pricing;

h) The increased integration and optimisation of the transport and energy systems to provide decentralised heat and power and enable widespread energy storage.

Whether or not these possibilities will be realised will depend greatly on future UK policies towards innovation and the environment, in ways discussed in the following Chapters.

2.5 Conclusions

To sum up, at the *macro-economic* level, a low carbon UK economy would be a more prosperous economy than it is today, and there is no evidence that the transition would disrupt the UK's growth prospects. The same is true for the world economy. But much will depend on our capacity to reduce costs through RD&D and innovation, in both energy production and use.

At the *micro-economic* level, impact on the energy, manufacturing and transport industries would be profound. The main effects, though, would be those of substitution. Reductions in value added and earnings opportunities in carbon-based industries are likely to be offset by rising value added and earnings opportunities in the low carbon industries and services that displace them. Cost savings in energy use would actually amount to a source of real income growth. These would include substantial indirect cost savings, for example, from reducing economic inefficiencies caused by urban traffic congestion.

Figure 2-1 Extrapolation of today's technologies for reducing CO_2 emissions

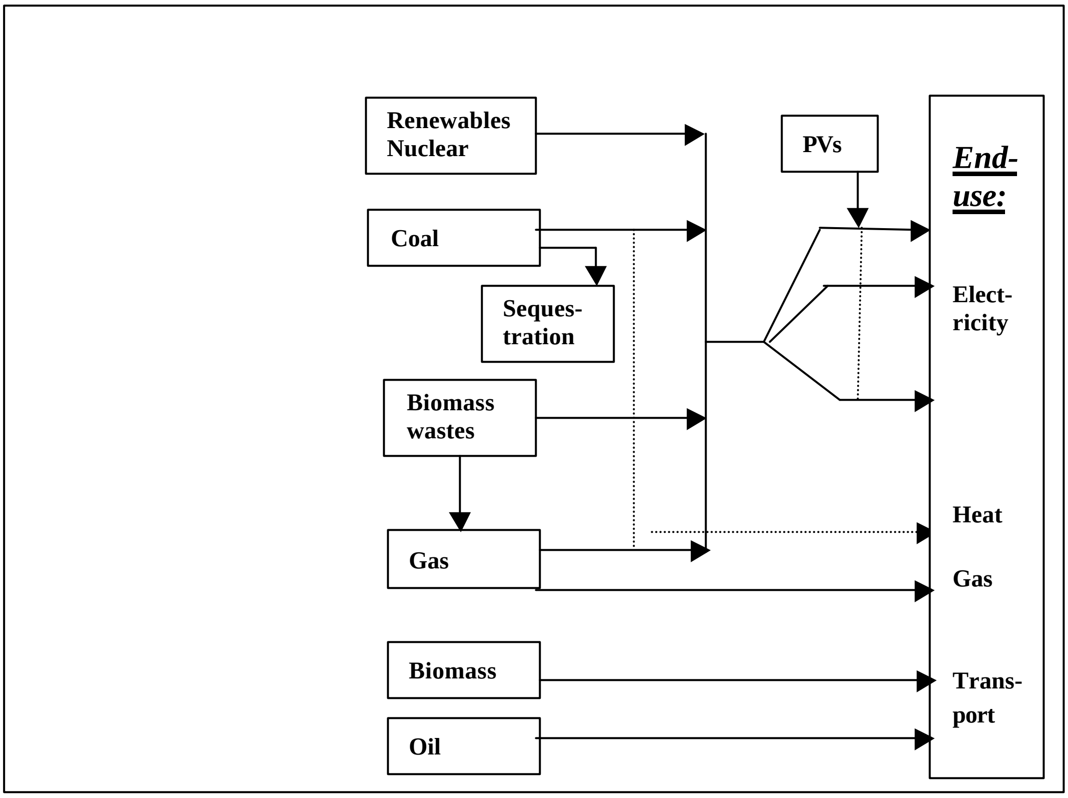


Figure 2-2 As for Figure 2-1, but with emerging options included (in blue)

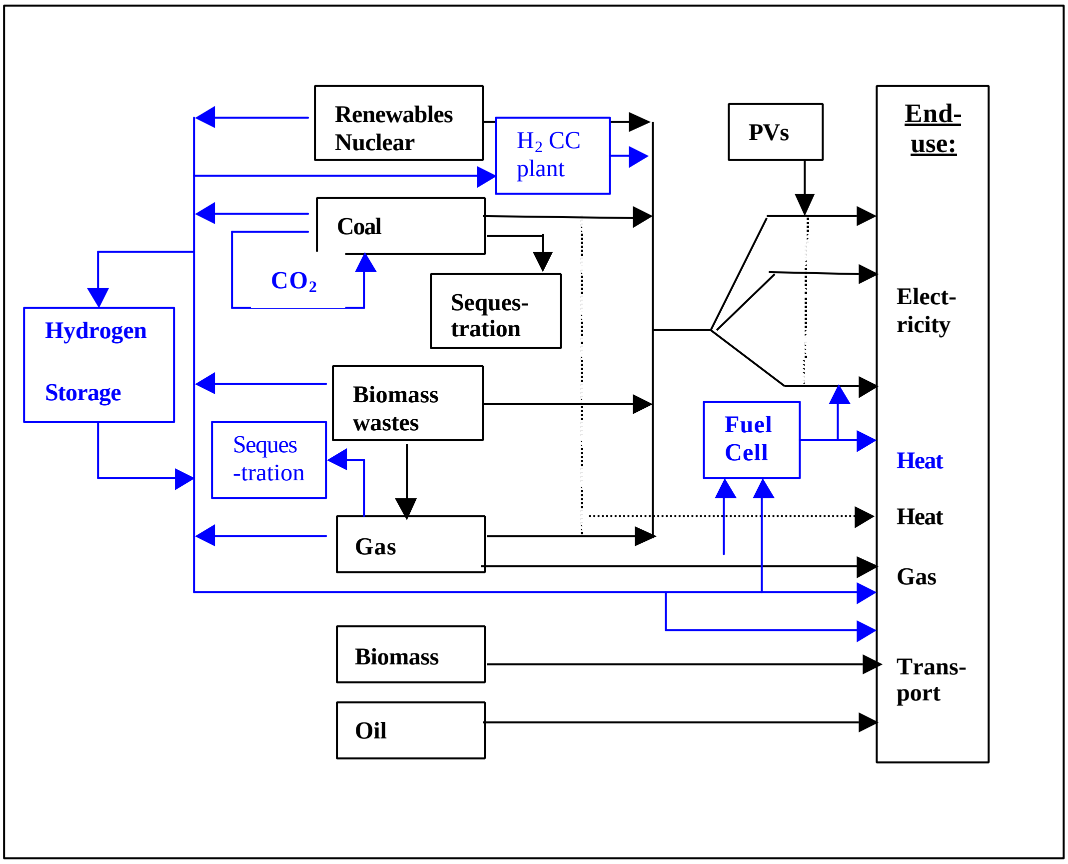


Figure 2-3 Low carbon economy - Efficiency in energy use

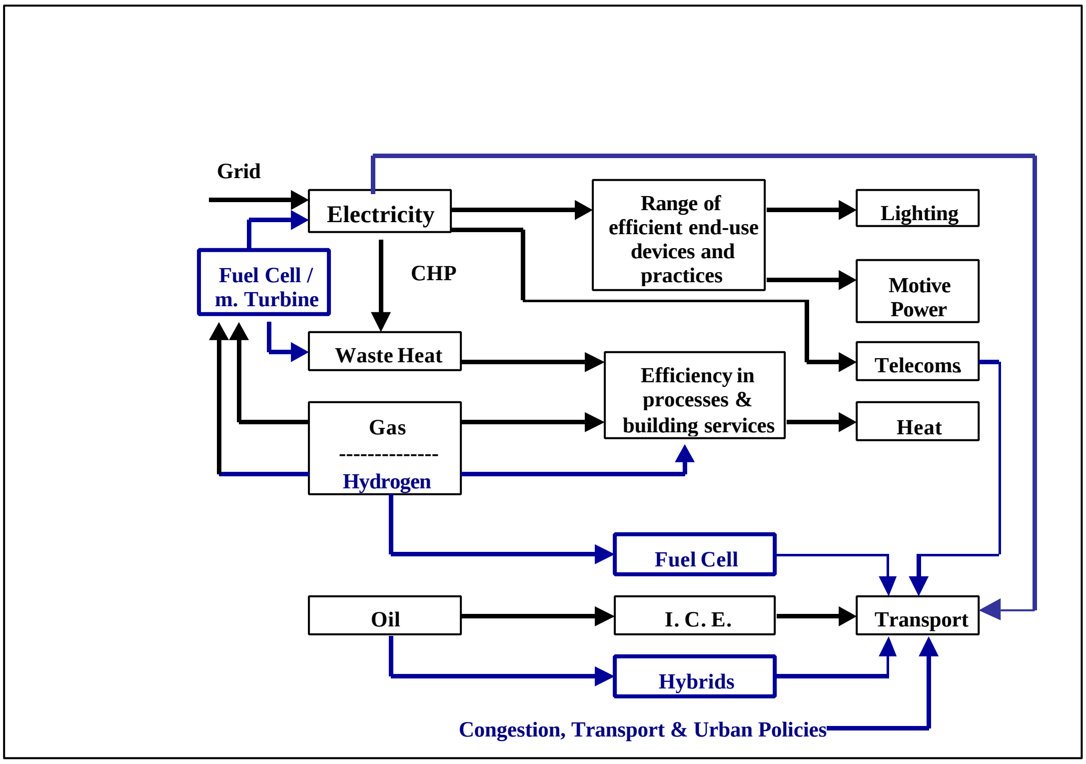
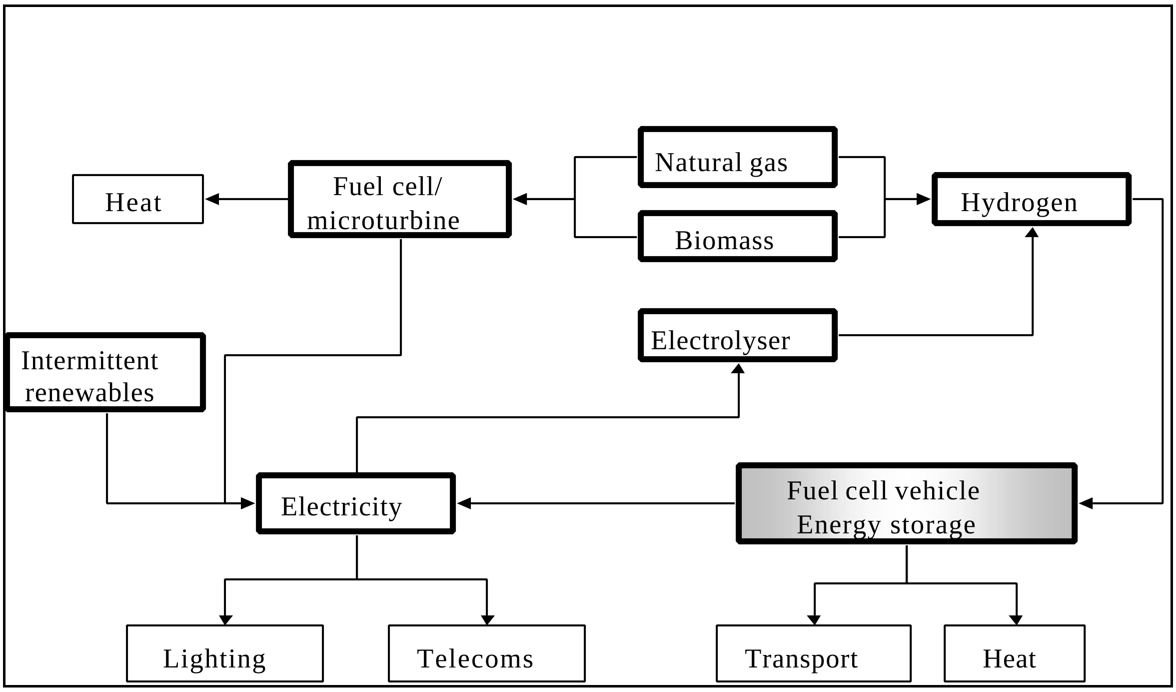


Figure 2-4 Transport and energy system integration : solving the storage problem



3 SCENARIOS AND PATHWAYS TOWARD A LOW-CARBON FUTURE

3.1 Scenarios

There is a wide range of possible low carbon futures for all countries—and an even wider range of pathways to them. Scenarios aim to provide a framework for imaginative and lateral thinking against which ideas and strategic decisions can be evaluated. In terms of scope, they may have a global or local focus, they may be evolutionary (tracing possible outcomes starting from a particular set of initial conditions) or prescriptive (tracing routes to achieving a particular chosen endpoint), and they may be quantitative or qualitative. Scenarios are particularly useful when trying to understand complex systems with incomplete information and to assess the implications of planned and unplanned change.

This chapter begins by reviewing a number of recent representative scenarios that describe alternative energy futures and identifies common drivers, assumptions and outcomes. Key global and UK-specific scenarios are reviewed.

3.1.1 Global scenarios

At the global level, the review by Inter-governmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios provides a good basis for analysis.[4] It summarises the features of over 130 studies with 450 emission scenarios for this century. Some show emissions rising exponentially from approximately 6 gigatons C today to 5 to 10 times this level by 2100. Others show emissions peaking in the range 6 to 10 gigatons C in the first half of this century and declining to negligible levels—or even negative levels, with sequestration—by 2100. Similar patterns have been found applicable to individual countries (see Anderson and Cavendish 2001). Close inspection of the methods and the data on which the scenarios are based show that differences between them turn critically on *the influence of climate change policies* on two assumptions:

- The rate of improvement of efficiency in the production, conversion and use of energy.
- The rate of decarbonisation of the energy supply mix.

More qualitative scenarios have been developed by both Shell, looking forward to 2020, and the World Business Council for Sustainable Development (WBCSD), which extend to 2050. These scenarios examine broad socio-economic trends, driven by the impacts of technological development, liberalisation of markets and increasing globalisation and inter-dependence on both individuals and institutions. Amongst the most detailed energy scenarios are those developed in the course of a five year study undertaken by IIASA and

[4] Nakicenovic et al.(Editors). Special edition of the journal: *Mitigation and Adaptation Strategies for Global Change*, Vol. 3, 1998

the World Energy Council (WEC)[5]. This study aimed to integrate near-term strategies through 2020 with long-term opportunities to 2100; analyse alternative future developments; apply a unified methodological framework using formal models and databases to ensure consistency and reproducibility; incorporate a dynamic treatment of technological change; and integrate regional aspirations with global possibilities. The scenarios fall into three groupings, with a number of variants emphasising differences in the driving forces:

- Case A represents a high growth world in which economic growth and energy consumption increases and energy efficiency improvements are strong:
    - A1 - emphasis on oil and natural gas use;
    - A2 - coal-intensive (with implications for severe local and regional pollution, and high carbon emissions, unless major and costly efforts are taken to tackle these);
    - A3 – emphasis on the roles of natural gas, new renewables and nuclear in averting serious problems from emissions;
- Case B represents a middle course, with intermediate economic growth and more modest technological improvements;
- Case C represents an ecologically driven scenario, with policy makers and other actors in society succeeding in promoting energy efficiency, technology innovation and transfer, non-fossil fuel development, and the reduction of institutional barriers:
    - C1 - emphasis on energy efficiency improvements, new renewables (especially solar in the longer run), but with nuclear power phased out by 2100 because unable to satisfy its critics;
    - C2 - nuclear power plays an expanding role.

The main features of the scenarios are outlined in the following table:

[5] Published as *Global Energy Perspectives* (Nakicenovic et al. 1998) and updated in the report by the UNDP/WEC: (2000)*World Energy Assessment: Energy and the Challenge of Sustainability*.

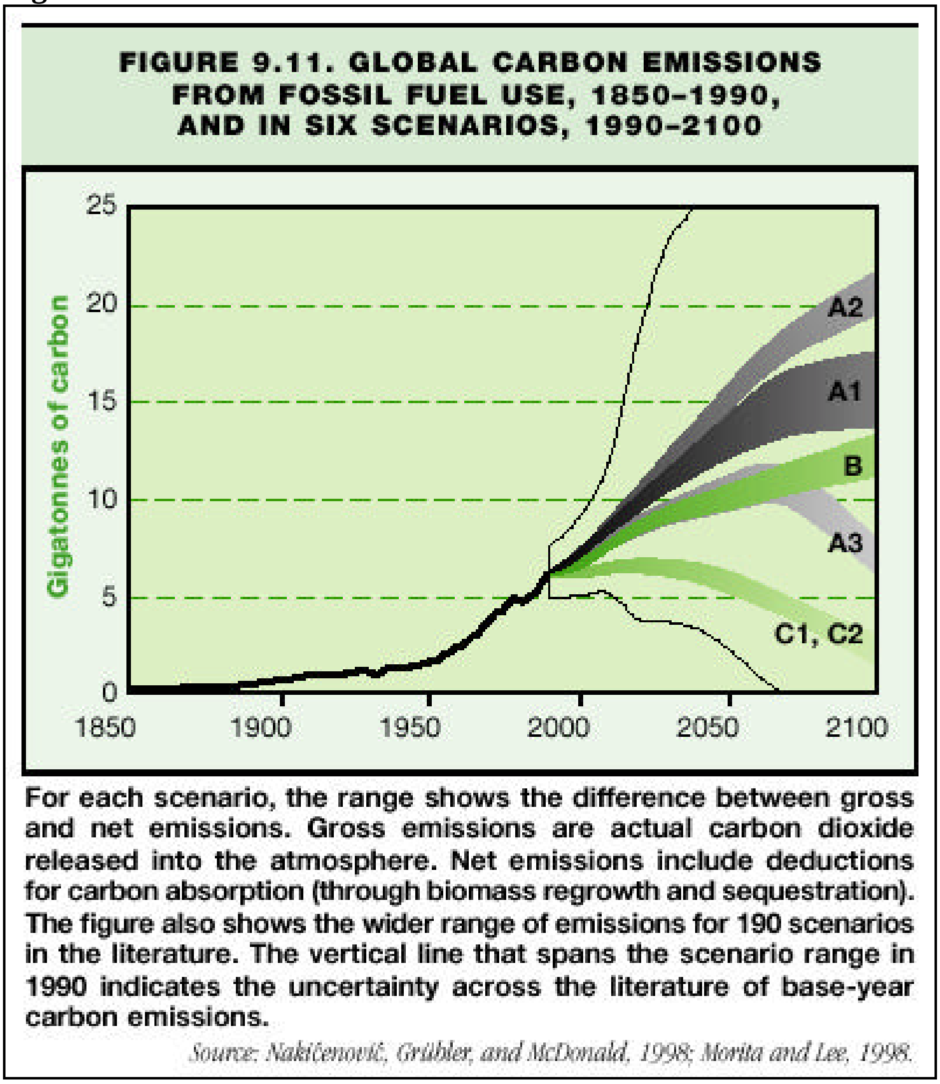
Table 3-1 Summary of Cases for Global Energy Scenarios

		Case A High Growth	Case B Middle Course	Case C Ecologically Driven
World Population 2050 (billions)		10.1	10.1	10.1
World economic growth 1990-2050 (annual growth)		2.7%	2.2%	2.2%
World energy intensity improvement rate 1990 - 2050 (annual percentage change)		medium -1.0%	low - 0.7%	high -1.4%
Carbon intensity 2050 (grams of carbon per 1990 dollar of gross world product)		90-140	130	70
Primary energy demand (Gtoe) 2050		25	20	14
Resource availability				
	Fossil	high	medium	low
	Non-fossil	high	medium	high
Technology Costs				
	Fossil	low	medium	high
	Non-fossil	low	medium	low
Technology Dynamics				
	Fossil	high	medium	medium
	Non-fossil	high	medium	low
CO_2 emission constraint		no	no	yes
Carbon emissions (GtC) in 2050		9-15	10	5
Environmental taxes		no	no	yes

Source: UNDP/WEC (2000), *World Energy Assessment*

The following graph illustrates global CO2 emissions under the different WEC scenarios:

Figure 3-1 Global CO2 emissions under WEC scenarios



Source: UNDP/WEC (2000) *World Energy Assessment*

Case C has the lowest energy consumption and greenhouse gas emissions trajectories of the three cases. Only scenarios C1, C2 and A3 achieve atmospheric CO2 concentrations less than double pre-industrial levels by the year 2100. These scenarios are characterised by rapid progress along technological learning curves.

Though the median estimate of economic growth is lower for the ecologically driven scenario C than for high growth case A, the authors recognise that there are considerable uncertainties surrounding these estimates. Scenario C includes policies and efforts leading to substantial technological progress and it is highly possible that, under these conditions, positive feedback effects could lead to unforeseen development and take-up of technical advances, resulting in economic growth as high or higher than that in case A.

3.1.2 UK Scenarios

The most widely discussed UK scenarios for the period up to 2050 are those recently developed by the Royal Commission on Environmental Pollution (RCEP) in their 22nd Report. The RCEP scenarios are prescriptive - they set a target for reducing UK CO_2 emissions and investigate the ways in which this target may be achieved over the next 50 years. As such, they are much more focused than the global scenarios. However, inherent in the approach is the need to make assumptions about key variables such as energy demand and the rate of diffusion and acceptability of new technologies. The principal advantage is that it describes what is possible given present-day technology and the current socio-political climate. However, this approach disregards factors that may cause substantial shifts in the business-as-usual baseline or change relative costings and so alter the scenario outcomes.

The RCEP developed four scenarios, aimed at achieving a 60% reduction in UK CO_2 emissions by 2050. The main assumptions common to all four scenarios are that:

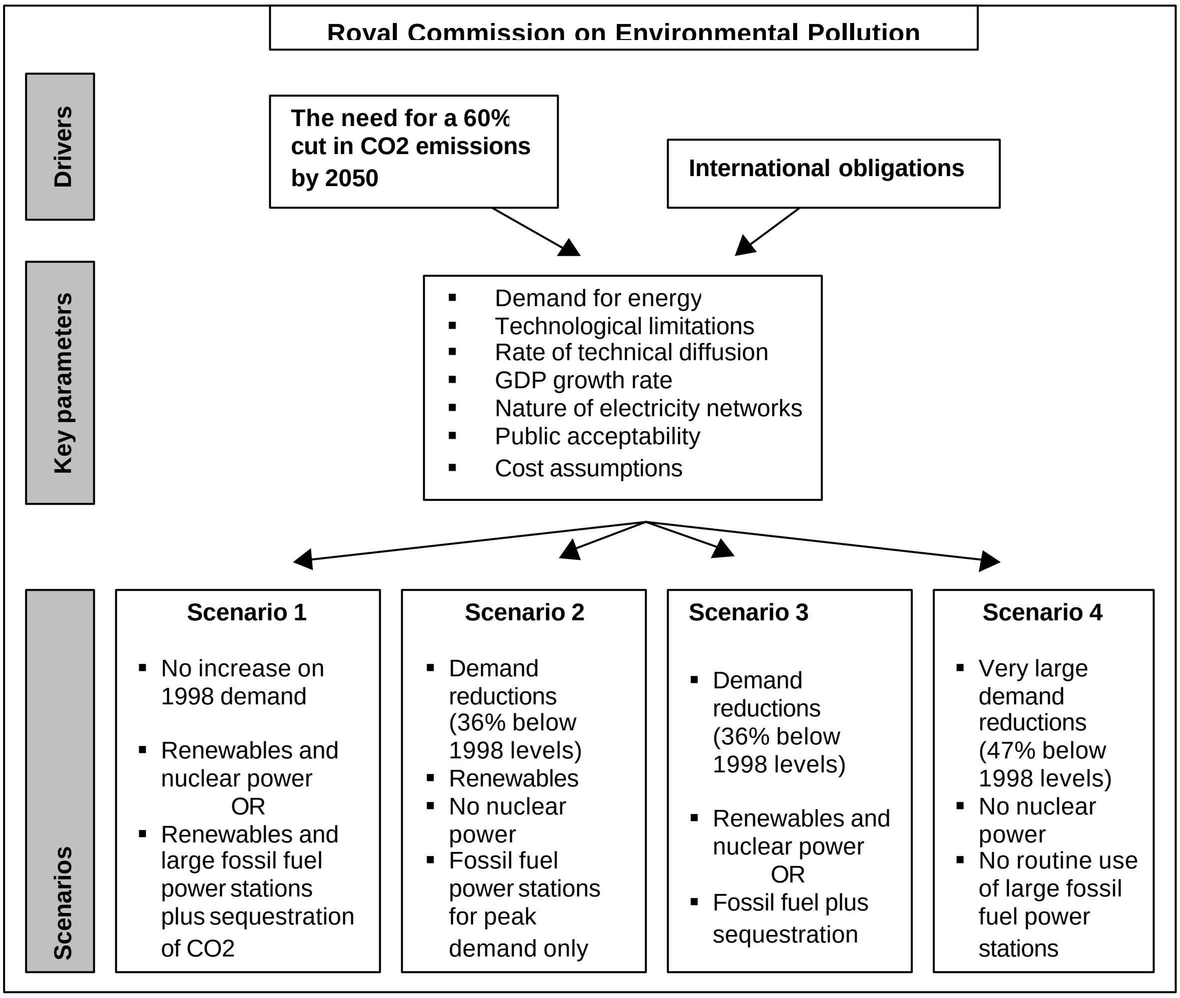
- oil remains the main transport fuel;
- fossil fuels continue to be used for high-grade industrial heat demands and some micro CHP;
- end-use demand is held constant or greatly reduced.

The scenarios differ in the levels of

- demand reductions assumed;
- fossil fuel use;
- deployment of renewables (onshore and offshore wind, energy crops, photovoltaics, small hydro and tidal power);
- use of nuclear power;
- CO_2 sequestration.

The RCEP scenarios are summarised below:

Figure 3-2 Summary of Royal Commission on Environmental Pollution scenarios



A complementary, more qualitative set of scenarios[6] has been developed by the Foresight Energy and Natural Environment Panel. These identify the main societal trends over the period 2000 to 2040, and aim to identify and highlight key opportunities and challenges posed by future changes in the supply and demand for energy and natural resources. These scenarios look at the effects on economic growth, energy consumption and costs, environmental awareness and policy, and technological change of different socio-economic drivers relating to more community or individualistic values and more global or local governance. These effects underpin a range of R&D challenges, identified as

- Network issues for distributed energy systems
- Development of more sustainable electricity generating technology whether conventional, renewable or nuclear
- Increased efficiency of generating technology including co-generation (CHP)
- Increased efficiency of end-use technologies
- Transportation technology, for example fuel cells and associated infrastructure

[6] Foresight Energy and Natural Environment Panel, *Energy Futures*, 2000

- Biomass and waste utilisation
- Large-scale energy storage
- Decommissioning of nuclear plant
- Redeployment of existing technology
- Social science investigation of social behaviour and attitudes to energy use
- Education to engender understanding and ownership of sustainable development
- Mechanisms to facilitate emissions trading
- Carbon dioxide sequestration
- Regulatory mechanisms and facilitation of investment in energy efficiency and reduction measures
- Improved fossil fuel extraction (conventional and unconventional)

3.2 Assessment of scenario drivers, outcomes and insights

Both UK and global energy scenarios have a number of common features. All explore alternative technological possibilities under alternative assumptions (sometimes implicit) about future socio-economic trends and the structure of energy markets. All aim to produce plausible and self-consistent stories about the future. The range of possible outcomes is greatly influenced by the various sources of uncertainty.

Although individual scenarios diverge over the assumptions that are made and the relative importance attached to the various parameters, a number of key insights nevertheless emerge . This is represented schematically in Figure 3.3.

The *key parameters and drivers* of the scenarios are economic, technological and social. Economic factors include the rate of liberalisation and deregulation, reduction of trade barriers, the rate of economic growth and regulatory and fiscal instruments imposed. Technological parameters include cost predictions and the rate of technological development and diffusion. Social drivers cover projections of energy demand, demographic changes and values held by society.

Sources of uncertainty include variation in rates of change of drivers and parameters, such as the rate and direction of technical diffusion. Other sources include the effectiveness of planned change; geo-political power shifts; technical lock-in and learning curve effects; shifts in societal values; impacts of environmental change; and time horizons of change. Uncertainties in turn lead to differing assumptions about economic and social factors in the course of developing scenarios: for example on the role of market-based and regulatory mechanisms on changes in individual and institutional behaviour; on the role of international trade and investment; on the rate of economic growth; on income distribution and equity; and on the effectiveness of political and institutional arrangements in the implementation of policies. Some scenarios assume that that historical trends are an effective guide to future patterns; however, it is common to ‘challenge’ the assumptions with other scenarios that assume marked departures from current trends.

The *common outcomes* of the scenarios are that:

- primary energy sources diverge - many fuel mix options are possible;
- final energy carriers converge - these will be more high quality fuels and grid-based transmission networks, supplying more efficient devices;
- energy used per unit of GDP decreases andeconomic growth de-couples from increases in energy consumption;
- demand for energy services increases - based on flexible and convenient forms of energy.
- Economic growth is generally high in all scenarios

Three *key insights* emerge from this assessment of the scenarios:

- Energy systems are non-linear:

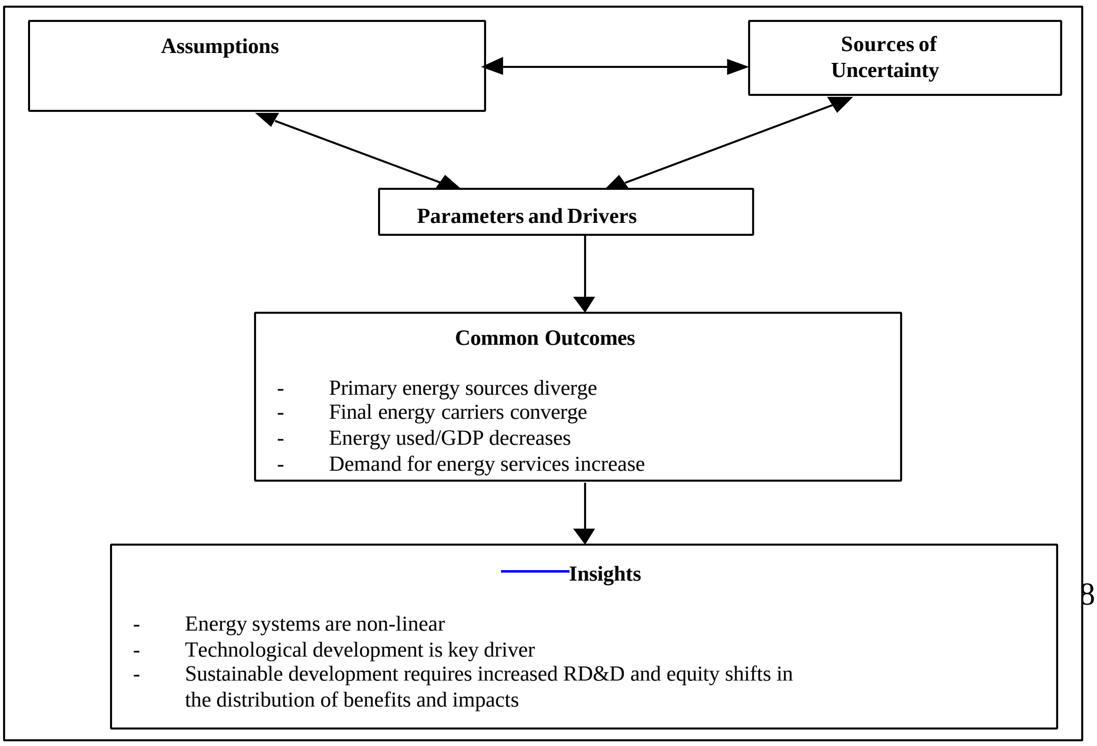
Major effects may result from small changes in end-use demands, development and take up of technologies, market structures or application of policies. Thus, periods of stability are likely to be short-lived or non-existent, and significant changes in energy demand and technology mix are to be expected.

- Technological development and take-up is one of the key drivers:

- Achieving sustainable development will require both significant increases in RD&D spending and major shifts to a more equitable distribution of benefits and impacts:

To balance economic, environmental and social objectives, whilst significantly reducing greenhouse gas emissions, will require concerted global action. For example, the Royal Commission on Environmental Pollution argues that long-term agreement should be based on convergence over a time scale of several decades towards a level of emissions which does not add to atmospheric concentrations and which is allocated to all nations on a per capita basis.

Figure 3-3 Scenario Approaches



3.3 Pathways toward a low carbon future

Pathways toward a low carbon future for the UK need to be considered on two time scales:

- For the medium term - up to 2010;
- For the longer term - out to 2050.

Different technologies and practices will be important on these two time scales, but the scenarios make clear the importance of putting into place now policies and measures to stimulate the development of technologies for the long term.

In international terms, the UK is in a strong position. UK greenhouse gas emissions were reduced by 14% between 1990 and 2000. The main drivers for these emissions reductions were wider socio-economic changes - the shift in economic activity from manufacturing to services, the relative decline in energy intensive industries, energy efficiency improvements in both industrial and domestic sectors, and the 'decarbonisation' of primary energy with the switch from coal and oil to gas powered electricity generation - rather than the direct result of policies.

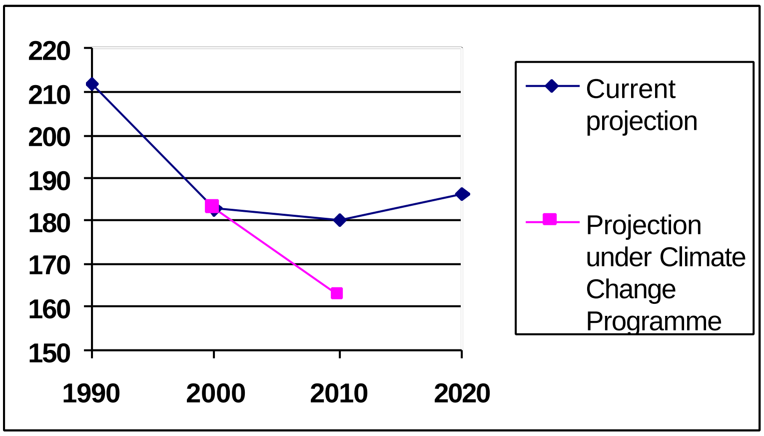
There is an underlying trend for emissions to begin rising again after 2010 due to retirement of nuclear power stations and the continued projected growth in transport emissions. Thus, there is a need for a clear vision of how the UK can make the transformation to a low carbon economy in the longer term.

For the medium term, the UK government has outlined the measures that it has and will put in place to ensure continued emissions reductions to 2010 (see Fig. 3.2). These are described in the UK Climate Change Programme (DETR 2000). The targets for the medium term for the UK are the legally-binding Kyoto target to reduce greenhouse gas (GHG) emissions by 12.5% below 1990 levels by 2008-2012, and the UK Government's domestic goal of reducing UK CO_2 emissions by 20% below 1990 levels by 2010.

The major reductions from 2000 to 2010 will be the result of climate-related policies, including the Climate Change Levy and associated energy efficiency agreements, the 10% Renewables Obligation, and the EU-level voluntary agreements on vehicle CO_2 emissions reductions. There is a need to ensure the successful take up of these measures in the short and medium term.

However, in the long term, 60 percent or larger cuts in GHG emissions may be required. As the scenarios show, such targets will require the development of different technologies and practices than are likely to be deployed in the medium term. A range of policies and measures will be needed to support these technologies in parallel with those for the medium term, in order to create options that would not otherwise exist, or bring them forward in time.

Figure 3-4 Projections of UK Greenhouse Gas emissions 1990-2020, MtC



Source: DETR (2000) Climate Change: the UK Programme

3.4 Conclusions

This Chapter reviewed a range of scenarios and pathways toward a low carbon future, both in the UK and in a global context. Whilst scenarios emphasise different drivers and parameters, three insights emerge from assessment of the scenarios:

- First, the non-linearity of energy systems makes prediction difficult, and uncertainties are very large, but major departures from current trends may result from changes, often initially small, in the development and take-up of technologies and in market structures.
- Second, technological development and take-up is identified as one of the key drivers across all the scenarios.
- Third, none of the scenarios reviewed above, and few if any of the very large number of peer reviewed studies cited in the IPCC Special Report on Emissions Scenarios, have identified any serious conflict between achieving low greenhouse gas emissions in the long term and economic growth.

However, the technological changes required to move onto a low emissions path are fundamental. Analysis of current and future UK emissions trends suggests that the successful application of emissions reductions policies, including stimulation of RD&D, will be required to maintain the UK on a pathway toward a low carbon future.

4 SETTING THEMATIC PRORITIES FOR RD&D INTO LOW CARBON TECHNOLOGIES AND PRACTICES

4.1 Introduction

The range of technological possibilities that could contribute to a low carbon future is exceptionally wide, and can only be outlined in broad terms. This is a positive result of the scenarios discussed in Chapter 3, since it means that the UK, in common with other countries, has a range of promising options to explore and develop in response to the climate change problem. By the same token, the breadth of the field for possible support by the Carbon Trust in the long term is so large that any attempt to prioritise individual technologies through a single review would be inappropriate. Instead, thematic priorities for the Trust's RD&D portfolio have been identified, and some ground rules by which projects might be screened and appraised have been suggested.

4.2 Method of Assessing Thematic Priorities

This section describes the framework developed, which is then applied in section 4.4 to give some initial indications of priority research themes. There will be a need for more detailed appraisal of options within those priority themes, for example as specific ideas are elicited from the research community through calls for proposals. The framework developed here should also provide a useful basis for that more detailed technology appraisal, although further considerations are likely to be important at that stage.

The criteria developed for the initial assessment of research themes fall within two areas:

Strategic impact – a measure of the impact that the intervention could have on meeting the strategic aims of the Carbon Trust, as reflected by the following factors:

- Significantly improves energy efficiency and reduces carbon intensity of energy production and use;
- Moves UK towards energy sustainability, by reducing energy dependence, substituting renewable primary energy sources, or being a key step on an evolving pathway to zero emissions;
- Improves competitive advantage with prospects of new business opportunities for UK;
- Maintains or improves UK's energy security;
- Broadens and deepens UK technological capabilities.

Deliverability – a measure of the extent to which the Carbon Trust can facilitate delivery of an advantaged position within the intervention, as measured by such factors as:

- UK's competitive position to exploit the technology to its advantage;

- Development status and technology potential;
- Number and severity of barriers to commercialization.

Annex 1 gives more details of how technologies are judged against these criteria. It should be noted that judgements are made on the basis of peer review by contributors with expert knowledge of current technological capabilities and potential. As such, they are, to a certain extent, subjective and will change with the development of each technology.

4.3 Messages from the Stakeholder Interviews

Stakeholder interviews were conducted with more than a dozen people to ascertain the perspectives of representatives from the main areas which will be influenced directly or indirectly by the Trust's operations: the Research Councils, industry (both energy supply and major energy-users), the financial sector, non-government organizations, consultancies in the field of energy, and the research community. Only two interviewees felt that RD&D should not be a priority for the Trust. The majority emphasized that the Trust should develop a "diverse and balanced" RD&D portfolio. The main messages are that the Trust should:

(i) *Support supply side projects—in renewable energy in particular—as well as energy efficient, demand side projects.*

(ii) *Include technologies and practices with good long-term prospects.* "Avoid going down the path of quick near-term fixes" as one interviewee put it. As the scenarios have shown in Chapter 3, the transition to a low carbon future will require a substantial development effort over a long period, involving technologies and practices for energy supply and use that mark a fundamental departure from those in use today.

(iii) *Economic and social research.* Social and economic changes, and policies, all have an appreciable influence over technology development and use, and it was argued that the Trust should not focus on technology development exclusively.

(iv) *Not confine the research to the energy sector.* Policies and developments in transport and buildings (to cite just two examples) are crucially important.

(v) *Support research on international as well as national policies, including RD&D policies*. This is in both the environmental and the economic interests of the UK.

The next two sections discuss these recommendations under the headings of technology options and practices and social and economic research. They are followed by a summary of the proposed thematic priorities of the Trust, and suggestions on the ground rules it might use to develop its RD&D portfolio.

4.4 Low Carbon Technologies

Low carbon technologies and practices are fertile ground for research, and there is considerable scope for invention and innovation at all points in the energy supply chain. It is possible to reduce emissions through:

- Increasing energy efficiency at each stage of the supply chain;
- Increasing energy efficiency at the point of use in delivering the energy service.
- Reducing the carbon intensity of the energy source through substitution or sequestration.

These generic routes to the reduction of carbon emissions are illustrated in Figure 4-1.

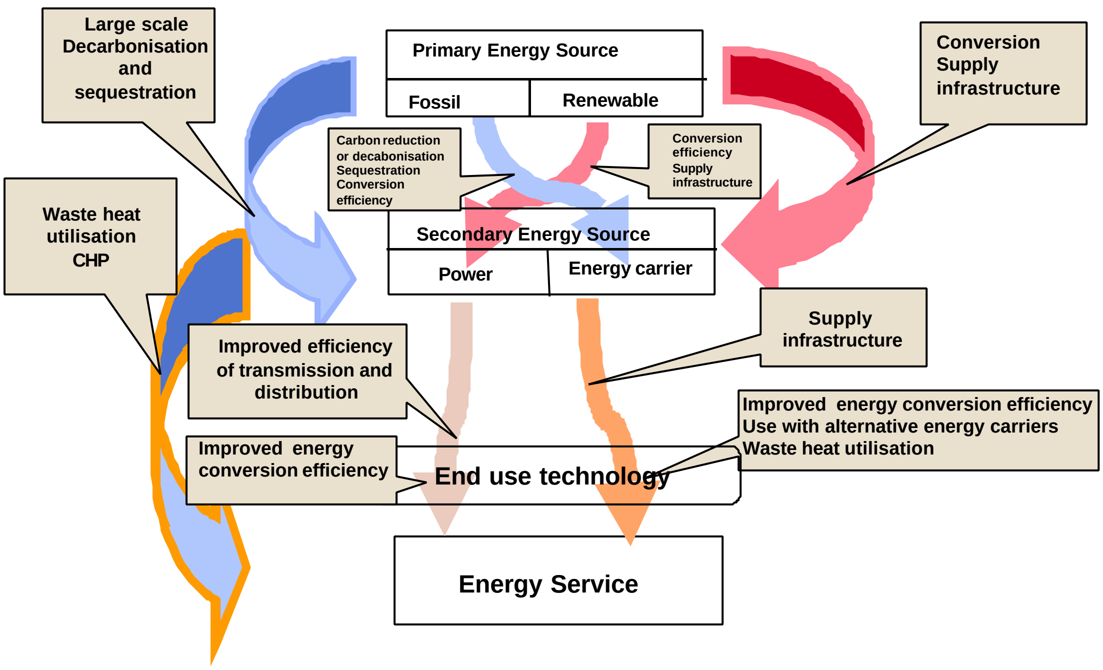


Figure 4-1 Energy Supply Chains and Potential Areas for Intervention

In an Appendix printed separately to this report we have provided assessments of several of the most important options, drawing on a wide range of business and academic literature, (e.g. ETSU (1994), AEA Technology (2001)), without attempting to be encyclopaedic. Beginning with efficiency in the use of energy they are:

- ***Energy efficiency in buildings***: Energy use in buildings accounts for one-third of energy use. Areas where RD&D can foster further improvements include heating and cooling technologies; efficient lighting; building envelope and architectural improvements (the latter including passive and active solar building designs);

building energy management systems; technologies that reduce standby losses; combined heat and power.

- ***Energy efficiency in industry***: Further potential for improvements in processes, heating, lighting and motive power, and more efficient processing routes (e.g. uses of membranes for separation and electro-technologies instead of combustion processes).

- ***Transport efficiency improvements***: Major efficiency improvements and emissions reductions are feasible through fuel cell and hybrid (petrol- and diesel-electric) vehicles. Congestion management and urban development policies are also important.

- ***Renewable energy***: There is a wide range of renewable technologies which could contribute to a low carbon future: photovoltaics; biomass (from crops and wastes); onshore, coastal and offshore wind; energy from tidal streams and waves; and hybrid wind-wave or wind-tidal stream devices.

- ***Energy storage systems***: for both stationary applications and transport. Their development is very important for the long-term resolution of the 'intermittency problem' of renewables.

- ***Hydrogen production, storage and use***: Developments here would provide a carbon-free fuel and a means of storing energy generated from renewable sources.

- ***Fuel cells for electricity generation and combined heat and power (CHP)***: these promise an efficient means of utilising energy from natural gas and/or hydrogen.

- ***Efficiency improvements in electricity supplies from 'clean' fossil fuels***: these include efficiency improvements in electricity generation and transmission, the use of coal-bed methane, loss reduction through the supply of fuels for fuel cells and micro-turbines for decentralised sources of CHP, and potentially the carbon free method of producing hydrogen for power generation and transport *if* coupled with:

- ***Carbon sequestration***: including geological storage of carbon dioxide.

- ***The social and economic aspects of a transition to a low carbon future***. Social and economic change will have an appreciable influence over technology development and use.

Several of the above technologies will affect several sectors, such as fuel cells for electricity generation and transport; and hydrogen for heating, electricity generation, combined heat and power and transport. Developments in sensors, controls and information technology, and in materials sciences and catalysis are also 'cross-cutting', and will directly or indirectly affect the prospects for all of the above.

Note that the relative lengths of the following sub-sections are not intended to indicate the relative importance of the technologies. Greater space has been given to topics that have received less attention to date, and which are generally less well understood.

4.4.1 Energy efficiency in buildings

Energy use in buildings accounts for approximately 30 percent of world energy consumption. Existing and emerging technologies and practices include:

- Natural light and ventilation systems.
- Building insulation, which has improved by a factor of >2 in the UK over the past 20 years.
- Further improvements in high insulation windows.
- Reductions of wasted energy in electrical appliances.
- Passive and active solar heating.
- Condensing gas boilers
- Combined heat and power systems.
- Micro-geothermal (heat pump) systems.
- PVs as architectural materials for roofs, cladding and windows.
- Use of local features—e.g. nighttime storage of 'coolth' underground.
- Information technology: (a) for providing energy producers and building owners with building performance information, and (b) energy management systems.

This list is not comprehensive, and is intended only to indicate the range of possibilities. This is also an area that will be affected by changing lifestyles under the influence of developments in information technology, for instance in the location of work, transport and the utilization of homes and offices. (See Section 4.5 on social and economic research below.) A summary of the impact of energy efficiency in buildings, and the UK's capacity to 'deliver' improvements, is provided in Table 4-1:

Table 4-1 Energy efficiency in buildings: impact and deliverability

Energy Efficiency – Buildings	Strategic Impact					Deliverability		
	Impact on Energy and Carbon Intensity	Impact on Sustainability	Effects on UK's Competitive Advantage	Impact on Energy Security	Impact on UK's Techno-logical capabilities	UK Competitive Position	Status and Techno-logical Potential	Barriers to commercial use
Building Envelope Improvements: Window and Insulation Retrofits	Moderate	Moderate	Low	Low	Moderate	Favourable	Mature	Low
Building Heating and Cooling Technologies	Moderate	Moderate	Low	Low	Moderate	Favourable	Mature	Moderate
Efficient Lighting	Moderate	Moderate	Low	Low	Moderate	Tenable	Mature	Low
Building Energy Management Systems	Moderate	Moderate	Low	Low	Moderate	Favourable	Mature	Low

In terms of its strategic impact, energy efficiency clearly has an important role in emissions reduction, and the UK has a good track record historically of improving or 'delivering' it. Further, all available evidence shows that there is considerable scope for further improvements using current 'best practice' technologies, and through the development of new technologies. However, there are limits to what it can accomplish over the long-term and efficiency, by itself, in buildings as in other sectors, cannot result in a low carbon economy. This is why it will be necessary for the Trust also to support the development of *zero-carbon* technologies on the supply side, discussed below.

4.4.2 Energy Efficiency in Industry

In the near term there are numerous efficient technologies that could reduce energy intensity and emissions in industry. Many of them are specific to individual industries, such as pulp and paper manufacturing, chemical processing or glassmaking. Others are common to several industries. The Energy Efficiency Best Practice Programme of the DETR has produced profiles of many cases where technological developments have led to efficiency improvements in the utilisation of light, heat and power in industry. The possibilities are too diverse to classify or summarise in a simple way.

Developing and implementing new, more efficient processes can substantially reduce emissions from energy use in industrial processes. Such processes can encourage new, higher-quality products while generating less waste and fewer undesirable by-products. Opportunities exist to improve process efficiency via advances such as more selective catalysts, further developments in advanced separation, improved materials and improved electric motor systems. A particularly attractive longer-term opportunity is the use of biotechnology and bio-derived chemicals and materials. For energy conversion, in the longer term fuel cells and gasification of biomass and in-plant residues are likely to have a large impact.

Developments in the enabling sciences such as chemistry, metallurgy and biotechnology will also foster the development of novel manufacturing processes. This knowledge, along with enabling technologies such as modelling and simulation, improved industrial materials, and advanced sensors and intelligent control systems, can result in both incremental improvements and fundamental breakthroughs. Likewise, developing and demonstrating micro-manufacturing systems (such as mini-mills and micro-plant) for flexible process configuration and on-site/just-in-place (similar to just-in-time) manufacturing can reduce emissions in the long term. Decentralized manufacturing using locally distributed resources offers the advantage of reduced transport of raw materials and finished goods.

Resource recovery and utilization offer further savings. An advanced concept is *industrial ecology,* in which a community of producers and consumers performs in a closed system. Fossil energy is conserved or energy is obtained from sources that do not give rise to greenhouse gas emissions; materials are reused or recycled. The raw materials and resources needed for manufacturing can also be obtained by designing products for ease of disassembly and reuse, using more recycled materials in finished goods, and selecting raw materials to eliminate waste discharge or undesirable by-products. Examples of developments that could facilitate this approach are new

- Polymers, composites, and fibres and advanced ceramics engineering techniques.
- Substitution of materials such as biomass for petroleum feedstocks in producing chemicals.
- Novel concepts such as integration of industrial facilities with other plants and with facilities for power supply and waste management could lead to "zero-emission" systems.

Thus the main message for the Trust is that it is likely to receive a large and diverse range of applications from industry and the research community for RD&D projects aimed at improving energy efficiency in industry. The environmental and economic benefits are likely to be significant (Table 4-3). But it will be necessary to distinguish between, on the one hand, those projects that are 'best practice' applications of already completed RD&D programmes, for which other sources of finance are available (see Chapter 5) and, on the other, those still requiring RD&D.

Our assessment of the strategic impact of energy efficiency in industry is the similar to that of energy efficiency in buildings (see section 4.4.2 above), and is summarised in the following table:

Table 4-2 Energy efficiency in industry: impact and deliverability

Energy Efficiency - Industry	Strategic Impact					Deliverability		
	Impact on Energy and Carbon Intensity	Impact on Sustain-ability	Effects on UK's Competitive Advantage	Impact on Energy Security	Impact on UK's Techno-logical capabilities	UK Competitive Position	Status and Techno-logical Potential	Barriers to comer-cial use
High-Efficiency Motors, Drives and Motor-Driven Systems	Moderate	Low	Low	Low	Moderate	Favourable	Mature	Low
High Efficiency Separation Processes (see Appendix 2)	Moderate	Low	Moderate	Low	Moderate	Favourable	Growing	Moderate
Advanced End-Use Electro-technologies	Moderate	Low	Low	Low	Moderate	Favourable	Mature	Low
District Heating and Cooling	Moderate	Moderate	Low	Moderate	Moderate	Weak	Mature	Moderate

4.4.3 Energy Efficiency in Transport

We classify the possibilities here under two general headings. The first, concerned with technological improvements in vehicles, namely advanced internal combustion engines, and electric, hybrid and fuel cell vehicles, are discussed in this sub-section. The second concerned with the development of transport management systems and policies, are discussed in Section 4.5 on social and economic research, include technical possibilities for improving transport management, such as electronic tolling and signalling, but the research agenda has a strong overlap with that on the social and economic side, for example urban development and congestion pricing and management policies.)

Advanced Internal Combustion Engines. There have been significant technological advances in the ICE during the past three decades; yet the potential for technology to reduce further still the environmental impact of conventional vehicles is far from exhausted. Substantial reductions can be expected from lean-burn combustion, direct-injection diesel engines, turbo compressors and inter-cooling, two-stroke engines, multi-valve heads, variable-intake valve control, advanced electronics and exhaust monitoring, four- and five- speed automatic transmissions, reduced accessory drive, lightweight materials, aerodynamic design, and better lubricants. 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 using a spark (gasoline-fuelled) or compression (diesel-fuelled) ignition cycle and will still use a conventional drive train and a conventional vehicle configuration.

For heavy-duty diesel engines, there is a strong inverse relationship between efficiency and reduction of non-CO_2 emissions. Many engine design options currently available to manufacturers for emissions reduction involve a fuel economy penalty of 10 to 20 percent. Significant technology advances are needed to allow the trend toward higher diesel-engine efficiency to continue in the face of increasing concern over non-CO_2 diesel engine emissions.

Electric and Hybrid Vehicles. Hybrid electric power trains for vehicles promise large emissions reductions in the near term. Electric vehicles use electric motors and batteries instead of internal combustion engines and fuel. Hybrid vehicles also use electric motors but rely on small internal combustion engines to provide electrical power. Therefore, the hybrid vehicle is still powered by gasoline or diesel fuel (or some alternative, such as natural gas, methanol or ethanol), but due to the system efficiencies of such an arrangement, relatively high fuel efficiency is achieved. The engine recharges the battery, so no external recharging is required. There are two advantages: (a) a significant improvement in fuel efficiency, since the engine can be run at the most efficient speed, and in some cases be switched off with the electric system taking over; (b) an appreciable reduction in environmentally damaging emissions, notably in the urban environment.

Fuel-Cell-Powered Vehicles. Fuel-cell-powered vehicles hold the potential for reducing transport emissions enormously in the decade after 2010. Fuel cells are electro-chemical devices that convert the chemical energy in fuels to electrical energy directly, without combustion, with high electrical efficiency and low pollutant emissions. They are similar in principle to primary batteries, except that the fuel and oxidant are stored externally, enabling them to continue operating as long as fuel and oxidant (oxygen or air) are supplied. The power system also includes a fuel processor and a power conditioner. The fuel processor converts fuels, such as natural gas, methanol, gasoline or bio-ethanol, into the hydrogen-rich fuel required by the fuel cell.

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. For the immediate future, proton-exchange membrane fuel cells (PEMFCs) (also called solid polymer fuel cells) appear to be the clear choice among fuel-cell technologies for light-duty vehicles, because they operate at moderate temperatures and have improved rapidly in power density and decreased in cost.

In the long-term, the combination of advanced fuel-cell technology and an infrastructure for supplying hydrogen offers the potential for a pollution-free propulsion system, depending on how the hydrogen is produced. The lack of adequate infrastructure and of on-board storage technologies for hydrogen is the greatest obstacles to its use as a transport fuel. Use of fuel cells in heavy trucks and locomotives will require a breakthrough in hydrogen production, distribution or on-board storage, or a breakthrough in reforming technology, before it will be competitive with the diesel engine. The drive-cycle thermal efficiency of current heavy-duty diesel-truck drive-trains is roughly the same (35 to 40 percent) as that for current methanol steam-reforming fuel-cell drive-trains (including the electric motor/controller and battery). Therefore, there is likely to be little incentive to switch heavy trucks to fuel cells until hydrogen fuel cells, with higher efficiencies (45 to 50 percent), become competitive and breakthroughs in hydrogen production, distribution and storage occur. Fuel cells may find acceptance in locomotives before they do in trucks, particularly as locomotives already tend to use electric power.

The gains in energy efficiency associated with the fuel cell—and also the hybrid-electric vehicles—deserve emphasising. Transport now accounts for roughly 40 percent of energy consumption. The internal combustion engine in the motorcar has an efficiency of roughly 15-18%. The fuel cell could more than double this. A two-fold increase in the fuel efficiency of the transport sector is a not an unrealistic aspiration in the longer term.

The following table provides an overall assessment of the importance of the vehicle technologies discussed, plus a comment on the—equally important—area of developments in transport management systems. The latter include technologies for congestion pricing and management, which could have a profound affect on urban development and resource efficiency such that an unambiguous reduction in the social and economic costs of transport is accompanied by major improvements in energy efficiency and major reductions in emissions.

Table 4-3 Transport efficiency improvements: impact and deliverability

Transport Efficiency	Strategic Impact					Deliverability		
	Impact on Energy and Carbon Intensity	Impact on Sustain-ability	Effects on UK's Competitive Advantage	Impact on Energy Security	Impact on UK's Techno-logical capabilities	UK Competitive Position	Status and Techno-logical Potential	Barriers to commercial use
Advanced Internal Combustion Engines	Moderate	Low	Low	Low	Moderate	Strong	Mature	Low
Hybrid Vehicles	High	Moderate	Moderate	Moderate	Moderate	Favourable	Growing	Moderate
Fuel Cell Vehicles	Very High	High	Very High	High	High	Strong	Growing	High
Low weight, low energy loss design	Moderate	Low	Low	Low	Moderate	Strong	Mature	Low
Traffic management systems	High	High	Moderate	Low	Moderate	Favourable	Growing	Low

4.4.4 Renewable energy

Renewable energy technologies have already been the subject of extensive reviews by Government Departments. (A new consultation exercise under the auspices of the DTI is actually underway as we write this report.) Significant experience with some technologies, especially biomass from crops and urban wastes, and onshore wind, was gained under the former Non-Fossil Fuel Obligation (NFFO) in the 1990s, which saw costs decline appreciably—in the case of wind, by six-fold—and operational performance greatly improved. In the same period, thanks mainly to programmes in other countries, the conversion efficiencies of commercial PV systems rose by 50% and costs declined by half, though they still remain high at roughly $5,000-10,000 per kW of peak capacity for an installed system. Appendix 2 provides some brief assessments.

The main points that we wish to bring to the Trust's attention are the following. On the positive side:

1) All the main technologies—photovoltaics, onshore and offshore wind, biomass and, to a lesser extent wave and tidal energy—are subjects of significant RD&D programmes in other OECD countries, for the good reason that their technological potential is appreciable. Given the quality of the science and engineering base in the UK, in industry and in the research community, we see no reason why the UK should be an exception. It is clear from our discussions with the stakeholders and others that many are looking to the leadership of the Trust in the development of the UK's RD&D portfolio in renewable energy.

2) Renewable energy holds out both the theoretical and the practical possibility for the attainment of a zero carbon economy in the long-term. In practice we may see a 'mixed' or diverse energy supply system, as the Shell scenarios and others have depicted (see Chapter 3), in which fossil fuels are used in conjunction with carbon sequestration and nuclear power (if the waste disposal and decommissioning problems can be overcome). However, the possibilities for renewable energy are appreciable, and the yield is much higher than is commonly thought. For example, the oil-equivalent yield of a PV system in UK conditions is roughly 300-370 tonnes per hectare—which is a hundred fold increase in the yield of land.[7]

[7] The oil-equivalent yield is the amount of energy required in a modern oil-fired power station to generate the same amount of energy per hectare as a PV. A PV device with 15% conversion efficiency would generate about 1.5 million kWh per hectare, which would require 375 tons of oil in a station with 33% thermal efficiency and 300 tons in a station with 41% conversion efficiency. The energy yield of a crop is usually less than 3 tons per hectare.

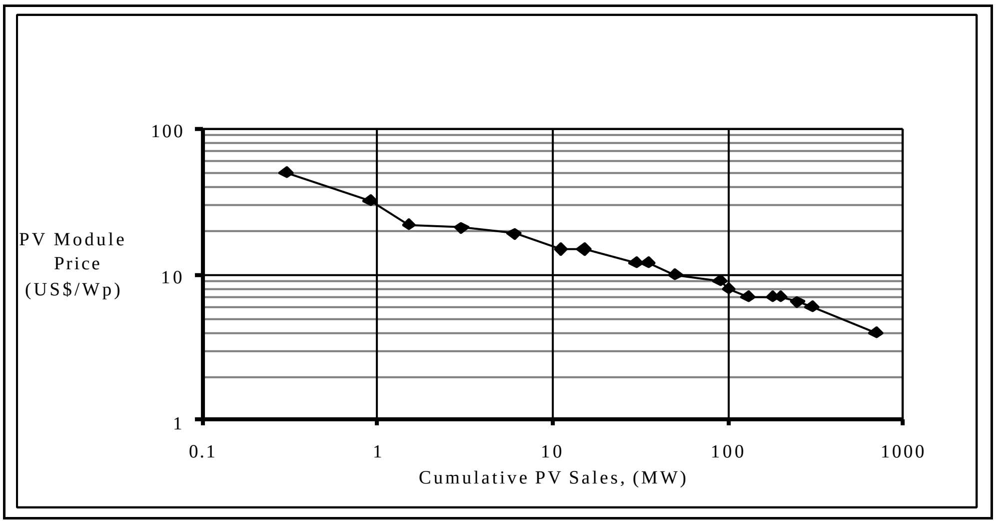


Figure 4-2 PV module prices as a function of cumulative sales, 1976 to 1997
Source: US President's Committee of Advisors on Science and Technology (1997), Appendix D, to which we have added an estimate for 1997 (the last point shown) based on data for that year.

3) The case for RD&D rests partly on the prospects for cost reductions through improvements in conversion efficiencies, and partly on the diversity of opportunities for improvement. The past twenty years have seen considerable progress. Each doubling of the cumulative volume of production, supported by RD&D programmes, has seen costs decline by approximately 20-30 percent for the key technologies. Currently costs are relatively high, except for wind and biomass. But renewable energy occupies only a small share of the world's energy markets; in the case of PVs, wind and offshore scheme, the share is presently less than 0.15 percent. Thus the prospects for cost reduction with further research and market expansion are appreciable. Figure 4.2 gives an idea of general trends for the case of PVs. Furthermore:

4) The technologies are modular, the lead times are short, and the possibilities for scale economies through batch or continuous production have barely been exploited. That a diversity of approaches is being pursued for each of the technologies—not least in such areas as offshore wind, tidal stream and wave energy devices—is also a healthy indicator that the technologies are fertile ground for innovation.

However, it would be misleading to present a wholly positive picture without acknowledging the risks and uncertainties:

5) Only very broad estimates exist of how much costs might be reduced through innovation. The World Energy Assessment (2000) gives the following estimates of for selected technologies, compared with the costs of grid electricity from fossil fuels; note that these costs exclude the added costs of storage in the case of intermittent forms of renewable energy (see sections 4.4.5 and 4.4.6 below):

Table 4-4 Current and potential future costs of renewable energy

Technology	Current cost (US Cents/kWh)	Potential future costs as the technology matures (US Cents/kWh
Biomass Energy:		
• Electricity	5-15	4-10
• Heat	1-5	1-5
• Ethanol	3-9	2-4
• (c.f. petrol and diesel)	(1.5-2.2) [c/]	(1.5-2.2) [c/]
Wind Electricity (onshore)	5-13	3-10
Photovoltaics [a/]	25-125	5-25
Solar Thermal Electricity [a/]	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	8-15	8-15
• Wave	8-20	Unclear
• Tidal streams	8-15	5-7
Grid supplies from fossil fuels (including transmission and distribution:		
• Off-peak	2-3	2-3
• Peak [b/]	15-25	15-25

Source: World Energy Assessment: Energy and the Challenge of Sustainability. UNDP and World Energy Council, 2000.

a/ For high insolation regions of the world (2000kWh/sq. metre/ year, about twice that of the UK)

b/ Varies with the spikiness of the peak.

c/ Crude price of $15-20 per barrel.

6) There is also the possibility of some negative environmental impacts. Biomass and onshore and coastal wind are especially vulnerable in this respect. For this reason, the development of offshore resources, including hybrid systems that utilize the energy from wind, waves, tidal streams and solar radiation need to be explored.

Our general assessment is provided in Table 4-5. The strategic impact of onshore (and coastal) wind, and of biomass, is likely to be much lower than for the other technologies discussed since they would run into far more serious land and environmental impact constraints if the attempt were made to deploy them on a large scale. It will take a significant and sustained development effort to take the offshore and PV technologies forward; but their strategic impact, in terms of the criteria discussed in Section 4.2, would be very high.

Table 4-5 Renewable energy: impact and deliverability

Renewable Energy Source for Power Generation	Strategic Impact					Deliverability		
	Impact on Energy and Carbon Intensity	Impact on Sustain-ability	Effects on UK's Competitive Advantage	Impact on Energy Security	Impact on UK's Techno-logical capabilities	UK Competitive Position	Status and Techno-logical Potential	Barriers to commercial use
Biomass	Moderate	Moderate	Moderate	Moderate	High	Favourable	Growing	Moderate
Onshore Wind	Low-Moderate	Low-Moderate	Low-Moderate	Low-Moderate	Low-Moderate	Favourable	Mature	Moderate
Offshore Wind	High	High	High	High	High	Tenable	Emerging	Moderate
Photovoltaics	Very High	Very High	Very High	High	High	Tenable	Growing	Moderate
Wave and Tidal Stream	Moderate	Moderate	Moderate	Moderate	Moderate	Favourable	Growinge	Moderate

4.4.5 Energy storage systems (for stationary applications and transport)

For electricity generation up to one quarter to 20 percent of the demand could be met by renewable energy without the need for storage systems. Electricity demands are already volatile, and the net effect of having an intermittent source of supply on the grid is to reduce average loads on fossil fuelled power plant without seriously affecting the *volatility* of the loads placed on them. Thus the intermittent nature of renewable energy supplies is not a serious *technological* constraint on their development in the near- to medium-term. However, for higher levels of market penetration, a solution to the storage problem will be crucial.

There is also an economic argument for the development of storage systems. Energy demands vary by time of day, day of week and season, often being highest when renewable energy is least available. For example, the average solar insolation in the UK is close to 1000kWh/m^2/year - 40% of that in the tropics. But it is seven times higher in Summer than in Winter, when energy demands, and also energy prices, are lowest. If then we could devise a system for storing the solar energy cheaply in large quantities in the summer the possibility would arise for 'harvesting' the resource for winter use. Similar remarks apply to wind. Wind energy is often abundantly available in winter; but there are calm periods and the energy is often unavailable in peak-demand periods when market prices are highest.

The use of renewable energy for transport will likewise require an economic solution of the storage problem.

The economic advantages of storage have long been recognized by the electricity industry, since it improves the economic returns to investments in fossil fuels and nuclear power. In the case of pumped storage, there is an improvement in the dynamic response of the system to changes in load or unplanned plant outages elsewhere, and a means of providing reactive power compensation. 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 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. Another is the heat storage device first introduced in many UK homes in the late 1960s, in which low cost ('half-price') electricity is used to charge the heater at night for use in the daytime. A recent and promising example is the regenerable fuel-cell system ('Regenesis') introduced at Little Barford Power Station by Innogy.

However, for the storage of energy on a major scale it has proved difficult to find means that would compete with the energy stored in fossil fuels. The large majority of PV systems around the world either use batteries for storage, which is indispensable for small systems, or are used to supplement grid power in sunny regions where there is a good co-incidence between the solar peaks and the demand peaks. These are important cases, but account for very small shares of the electricity market.

Options for further development include:

1. Batteries. (Small scale, short-term storage.) Much progress has been made on battery storage; but even advanced batteries only store as much energy per 50-100 kg of weight as is contained in roughly 1 kg of oil, which restricts their use to special purpose applications.

2. Advanced flywheels using carbon fibres. (Small and medium scale, short term storage.)

3. Pumped storage. (Large-scale, short-term storage.)

4. Compressed air storage. (Large-scale, short-term storage, extensively studied in the 1960s.) Often discussed in connection with wind energy, in which the compressed air could either be used in a large air-turbine generator, or to substitute for the compressor part of a gas-turbine power plant.

5. Thermal storage. (Small and medium scale, short term storage.)

6. Thermo-chemical storage. (Short- or medium-term storage, medium scale.) Use of high temperature solar energy from concentrators to create a synthesis gas from methane and CO_2, which can be desynthesised to give up the stored solar energy; pioneered by the Weizmann Institute in Israel; only suitable for high temperature solar concentrator systems in very sunny climates.)

7. Superconducting magnetic storage.

8. Electrical 'supercapacitors'. (Small-scale, short-term storage.)

9. Electro-chemical storage (in electrolytes) for use in fuel cells. The most promising example is the regenerable fuel-cell system pioneered by Innogy, noted above. (Intermediate scale in the 10s of MW range, suitable for short-term storage.)

10. Hydrogen production and storage. This is undoubtedly the most promising long-term option, long sought after by engineers and scientists. Suitable for short- or long-term storage on a small scale for local use, or large scale for general use. There are several options being explored internationally:

   - Seasonal storage in depleted natural gas and oil reservoirs and deep saline aquifers. Can also be injected into gas reservoirs—the 'hythane' option.

   - Short term storage in a liquid form (the boiling point is very low, however, about minus 250^o C), as a gas in pressure cylinders or storage tanks, in metal hydrides, through adsorption in metallic compounds, or through the chemical formation of synthetic hydrogen compounds.

   Hydrogen is also the ideal fuel for fuel cells for electricity generation and fuel cell vehicles. It can be distributed through gas grids, and become a source of decentralised heat and power using fuel cells or micro-turbines. It also has much potential for use in advanced combined cycle power plant for electricity generation. It is discussed further below (in 4.4.6).

All of the above are technologically feasible and in most cases have been demonstrated, and most are in use for special purposes. The production, storage and transmission of hydrogen by pipelines has long been used by the chemical industry.[8]

Data on costs are scarce and often rely on engineering assessments and projections. Some estimates are provided in Table 4-6.

Table 4-6 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.

Our assessment of the strategic importance of developments in storage systems is—*fundamental*. They would open the gate to very wide deployment of renewable energy

[8] See Justi (1987) *A Solar-Hydrogen Energy System*. New York: Plenum Press. Chapters 9 and 10, who reports on 60 years of operating experience in the chemical companies with hydrogen pipelines in Germany.

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 to which we now turn is so important.

4.4.6 Hydrogen production, storage and use

Hydrogen is a carbon-free energy carrier that has potential uses in many applications. For example, it can fuel vehicles, provide process heat for industrial processes, supply domestic heating needs through cogeneration or heat recovery systems, and fuel power plants for centralised or distributed generation. It burns cleanly and efficiently and can be used in modified conventional combustors to ease the transition to a completely new energy infrastructure based on the hydrogen in fuel cells or gas turbines for energy conversion. The level of CO_2 emissions reduction compared with conventional technologies will depend on how the hydrogen is produced. When it is produced via electrolysis of water using nuclear or renewable electricity, CO_2 is absent from the fuel cycle. It can also be produced directly from gas, coal bed methane or gasified coal, with the carbon being sequestered.

Expanded RD&D is needed on biological, thermochemical and electrochemical processes for producing hydrogen. Research is also needed on hydrogen storage technologies such as those based on innovative materials – for example, carbon fibres and structures and metal hydrides.

Cost of hydrogen

There are two elements in the hydrogen cost equation - cost of manufacture and cost of distribution to the end user. The equation is further complicated by choice whether to make hydrogen centrally and distribute - either as a high-pressure gas, stored in a convenient medium or cryogenically as a liquid - or to make it on-site in small plant. This provides a number of possible pathways to examine. In this section we compare the costs of manufacture from a variety of raw materials in both small and large plant, the costs of distribution and finally the delivered costs to the end user

Manufacture. Because of its presence in so many compound forms it is possible to make hydrogen from almost anything - all hydrocarbon fuels, biomass and water. The processes that must be used have all been shown to be technically feasible, though many of them require great improvements before they can be economically introduced. The following table summarises the costs of some processes that have been analysed in depth.

Table 4-7 Current and projected costs of gaseous hydrogen (ca 20 bar) $/GJ

	Near term	**Long term**	
Renewable sources			
Hydrogen from biomass gasification - large plant (18,000GJ/day ca 60Mscfd)		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

Sources: 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. also Gregoire-Padró and Putsche, Survey of the Economics of Hydrogen Technologies, National Renewable Energy Laboratory 1999.

In the short term, producing hydrogen from natural gas by steam reformation is the cheapest method and one of the cleaner methods involving hydrocarbon-based processes. In the longer term biomass gasification offers production at a competitive cost if current developments can be brought through into commercialisation.

The price of photovoltaic (PV) cells is declining steadily with the advent of new technology and increased use: costs have declined by about 30% with every doubling of cumulative production. In the long term this may be the most economic way to produce hydrogen renewably. It requires only limited water supplies to make large volumes of hydrogen, meaning that currently unused semi-arid areas can be employed productively. The amount of land used is not prohibitive and calculations show that a total area of only about 10,000 sq km could provide sufficient hydrogen for most of the world's current energy requirements, using projected solar PV efficiencies. Solar energy is not likely to provide the only primary source for hydrogen generation. Biomass, wind energy and hydroelectricity all have a part to play and will ensure that overall land use is not excessive.

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 further research development before they can be employed to produce useful amounts of hydrogen.

Storage and transportation. In the long term moving hydrogen around is best done using a pipeline, one that is similar to those used for natural gas. This will require a considerable investment in infrastructure and is unlikely to be achieved in the short term, apart from the dedicated pipelines that connect large producers and consumers of hydrogen at present in France, Germany, the US and Canada. However, 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 ca 15-20% hydrogen by volume, before modification of existing burners and other end-use technologies is required.

In the near term there are a variety of pathways by which hydrogen could be delivered to the end user. The biggest problem arises from its low volumetric energy density. All pathways seek either to increase in some way. Possible pathways include:

1. Central manufacture and distribution as:
   - Cryogenic liquid
   - As a gas in high pressure containers (operating at some combination of pressure and temperature to minimise costs and maximise energy density)
   - Physically adsorbed or combined as a hydride
2. Central manufacture of a hydrogen rich carrier which can be more effectively distributed and from which the hydrogen can be easily recovered at the central re-fuelling site:
   - low molecular weight hydrocarbons (natural gas, LPG, naphtha etc.)
   - Methanol or ammonia
3. Manufacture by local electrolysis of water using off-peak electricity

It is estimated that, using current technology, hydrogen would cost roughly $11-15/GJ for a refuelling outlet servicing 300 cars/day (Gregoire-Padró and Putsche, 1999). For comparison the cost of gasoline delivered to a retail outlet is $4-6/GJ ($14 -$20/bbl crude price). A hydrogen fuel cell vehicle would have two-to-three times the energy efficiency of a conventional ICE. Under this scenario, fuel costs per mile become comparable.

Using hydrogen. Hydrogen will burn in IC engines, turbines and gas boilers in the same way as the primary hydrocarbon (HC) fuels, but can also be used directly in fuel cells at high efficiency to provide heat and electrical outputs. 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. Safety is sometimes raised as an issue, but all analysis and operating experience so far shows that this is not a factor to be weighed against it as compared with other fuels.

The main issue with hydrogen is that it is a gas with very low volumetric energy density. Distribution and storage (either in bulk form e.g. retail sites and distributed power, or on board vehicles) are complex, costly and inefficient processes as evidenced by the cost data provided in the previous section.

As noted the ideal way to distribute bulk hydrogen is by pipeline and, although pipeline systems do exist, they are small compared with the extensive natural gas systems (e.g. the US has 2m km of natural gas pipeline to which 96% of the population has access).

Mixtures of hydrogen and natural gas, up to 20% volume hydrogen, offer some benefits when burned in an IC engine and can use the natural gas networks. Such mixtures, often referred to as hythane, may present an entry option for bulk hydrogen.

Storage issues 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. Since the primary focus of this work is vehicle use of hydrogen, gasoline is generally taken as the benchmark.

Figure 4-3 and notes summarise the present sate 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%.

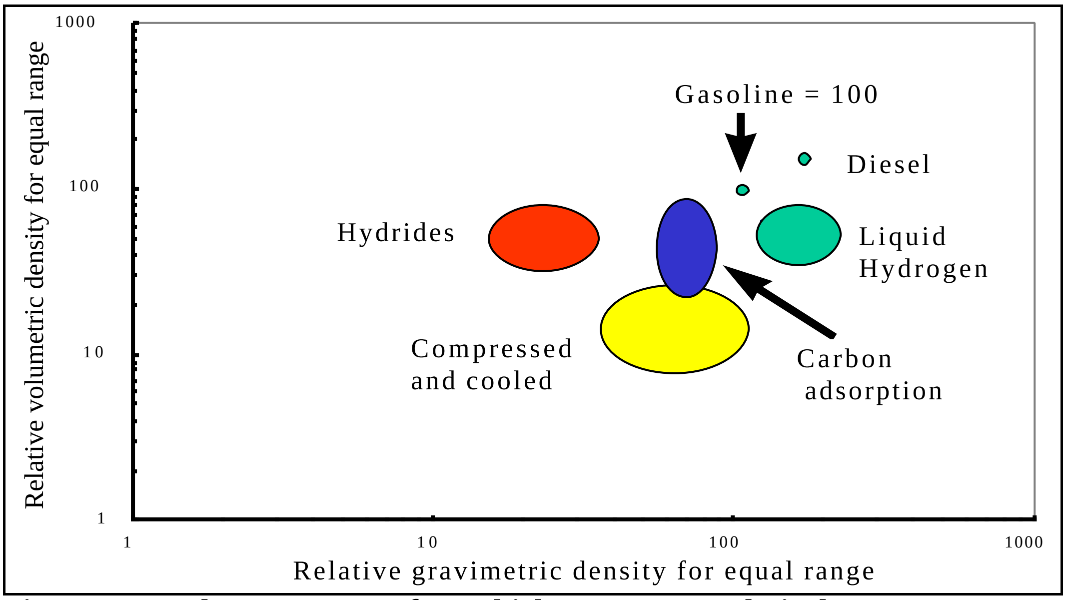


Figure 4-3 Hydrogen Storage for Vehicle: Current Technical Status

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.

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

Table 4-8 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

Summing Up: If a low carbon economy is to be attained in the long-term, the development of the hydrogen option will be crucial. This is not a new conclusion—it was central to the idea of the ‘nuclear economy’ four decades ago, when it was envisaged that nuclear energy would be used to generate hydrogen for transport, and it was revisited again during the oil price shocks of the 1970s. Developments have continued, however, and much progress has been made. It remains an important area for RD&D, not least on account of the promising developments in the fuel cell.

4.4.7 Fuel cells [9]

Fuel cells for electricity generation 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 two 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 an equivalent CCGT plant. The long term potential for a two-to threefold efficiency gain when used for transport has already been noted.

- *Low or Zero CO_2 Emissions*. Fuel cells are a key technology on an evolving strategy to a low carbon economy. They are a complementary technology for hydrogen as an energy carrier. They will probably be introduced initially with natural gas using integrated reformers and then fed directly with hydrogen as a hydrogen infrastructure is established. Further possibilities are hydrogen derived from coal, coal bed methane or gasified coal, with the CO_2 emissions from the gasification process being sequestered.

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)

[9] See also the discussion on fuel cells for transport in Section 4.4.3

- 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 (AFC, PAFC) or are near commercialisation (SPFC), 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 operated on a range of hydrocarbon fuels, do not require expensive electro-catalysts, and generate useful heat. They are thus 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. There is on-going research to develop intermediate temperature SOFCs, for example, 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. It is beyond the scope of this study to give a more detailed review, which can be found elsewhere.[10]

Instead, we would simply emphasise the their economic potential. 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. There are also likely to be synergies between the various applications, which may help to reduce costs further. Developments in the transport sector are likely to affect developments in the power sector and vice versa, not least because each will be a stimulus to the development of the infrastructure for fuel-cell technology and for the supply of hydrogen.

Current costs are well above conventional technologies in most areas, though this varies with the type of fuel cell. All fuel cell costs are presently high, which is not untypical of an emerging technology: estimates range between 500 and 10,000 dollars per kilowatt (a mature technology such as a gas turbine costs about $400-600/kW). But with further development and once in mass production it is estimated that they could cost as little as $30/kW for transport, matching the internal combustion engine, and $300/kW for stationary power. Table 4.9 gives an indication of current costs of the technologies and those predicted for mature systems by the companies involved.

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[10] See Nigel Brandon and David Hart (1999). An Introduction to Fuel Cell Technology and Economics. Imperial College Centre for Energy Policy and Technology. Occasional Paper No. 1. Obtainable from the Centre or on its website: www.iccept.ic.ac.uk. The DTI are also in the midst of a consultation exercise on fuel cell development (along with other technologies).

Table 4-9 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

If used for decentralized generation or CHP, there would be further substantial savings on both the capital costs of and the losses in electricity transmission and distribution. Studies suggest that with a standard natural gas price of about 2p/kWh, electricity could be generated for perhaps 4p/kWh, undercutting nearly halving the costs of electricity to household consumers. Such developments would be economically extraordinary, a paradigm shift in the industry. They they lend support to the view that responding to climate change may eventually prove to be economically beneficial, even ignoring the external benefits of the mitigation of climate change itself.

Our assessment of the strategic impact of the development of fuel cells is thus—fundamental, according to all the criteria we have used in this analysis. The strength of the engineering and scientific base in the UK also argues for a sound RD&D programme. A barrier to their introduction and use may be the regulatory policies of the industry—will net metering and pricing policies discriminate against the technology for example?

4.4.8 Electricity supplies from fossil fuels

There are two ways, not so far discussed, by which the fossil fuel industry might respond to climate change. The *first* is through efficiency improvements in the use of coal and gas for electricity supply; the improvements can be achieved in the power plants themselves, and in distribution and transmission. The *second* is the separation of hydrogen from carbon at source, which opens the route both to the provision of hydrogen for power generation—in gas-fired power stations, and in micro-turbines and fuel cells for distributed generation—and to a more economical means of carbon sequestration. It may well be that the industry, with the support of other Government programmes and policies, may shoulder the responsibilities for such development, as has happened so far; however, this scoping study would be incomplete without a discussion of them.

Both have received much attention, and are discussed further in the annex. In brief the possibilities include:

1) Further development of natural gas combined cycles. NGCC power-generation systems are highly promising for emissions reduction in the near term, as they were in the 1990s. They have three important advantages over other options: high efficiency, low levels of local pollutants and greenhouse gas emissions, and low installed capital cost. They are also attractive over a wide capacity range (megawatts up to hundreds of megawatts). NGCC is highly competitive in cost, cleanliness and efficiency in conversion. The combustion turbine with or without combined-cycle technology is relatively inexpensive and can be put in place quickly. NGCC 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.

2) The generation of electricity from coal based on integrated gasifier combined cycle power plant. IGCC systems combine two established technologies: coal gasification for the production of synthesis gas (a gas mixture containing mainly carbon monoxide and hydrogen) and NGCC power production. Synthesis natural 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 five major demonstration projects (two in Europe and three in the United States) are about 40 - 43 percent. Coal-fired IGCC technology is not currently competitive with large PF power stations, but development projects under way aim to increase efficiency and substantially reduce costs. An advanced process design could increase system efficiency to 47 to 49 percent by about 2005. In the long term, efficiencies greater than 60 percent are possible.

   The technology reduces 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%. In the near term the technology is not competitive with NGCC where gas is available. Unless environmental benefits are factored in, it also offers little economic benefit compared with steam stations using pulverized coal. 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.

3) 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.

An emerging area—of special relevance to the preceding discussions on fuel cells, micro-turbines, and PVs—is supporting research on the management and control of *decentralized forms of electricity generation and combined heat and power*. This is of much interest to industry in light of the technical developments discussed. How will electricity grids operate with perhaps tens of thousands of small-scale generators on the system? What will be the problems of control and dispatch? What will be the effects on the quality of supply (e.g. waveforms, reliability and voltage)? How will back-up supplies be provided? What safety problems will be encountered? And so forth. Although the distributed generation and CHP offers the prospects of significant reductions in the electrical losses associated with electricity transmission and distribution, and the other advantages discussed above, a number of technical questions remain to be answered.

The strategic impact, as we have defined it, of developments in electricity supplies will vary with the type of development (Table 4.10). The efficiency of power generation increased 10 fold over the last century, and there were major reductions of losses; there is every reason to expect further improvements, without the intervention of the Trust. However, there are two areas of special interest to the Trust: the possibilities for decentralized forms of power generation from fuel cells and micro-turbines; and hydrogen production from coal gasification and natural gas, in connection with combined cycle power plant.

Table 4-10 Technical Developments in Electricity Supplies from Fossil-Fuels: Impact and Deliverability

Clean Fossil Fuel Power Generation	Strategic Impact					Deliverability		
	Impact on Energy and Carbon Intensity	Impact on Sustain-ability	Effects on UK's Competitive Advantage	Impact on Energy Security	Impact on UK's Techno-logical capabilities	UK Competitive Position	Status and Techno-logical Potential	Barriers to commercial use
Natural Gas Combined Cycles (NGCC)	High	Moderate	Moderate	Low	Moderate	Favourable	Mature	Very Low
Integrated Gasifier Combined Cycles (IGCC)	Moderate	Moderate	Moderate	Moderate	Low	Weak	Growing	High
Improved Transmission and Distribution Systems	Low	Moderate	Low	Moderate	Moderate	Favourable	Mature	Very Low
Decentralised Power - Fuel cells	High	High	Very High	High	Moderate	Favourable	Growing	High
Decentralised power - Microturbines	Moderate-high	Moderate	High	Low	Moderate	Favourable	Growing	Moderate

4.4.9 Carbon Sequestration

Geological storage of CO_2 is the most promising sequestration technology for the near term. It involves capturing the gas and injecting it into subsurface repositories such as deep coal beds; depleted oil and gas reservoirs; and deep, confined saline aquifers. Other options are also being investigated, including deep ocean storage. However, the large uncertainties in its prospects have led to a greater focus geological storage.

CO2 separation is most economically achieved at source (e.g at source, e.g. in what is called steam reforming of gasified coal or natural gas to yield CO_2 and hydrogen streams). 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. 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 300m.) 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 CO2 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 injection into depleted oil reservoirs is a mature technology, as it is widely used for enhanced oil recovery. CO2 separation and sequestration in coal beds (for enhanced methane recovery) should be given a much higher priority for RD&D. (Table 4.11.)

Table 4-11 Carbon Separation and Sequestration: Impact and Deliverability

Carbon Sequestration	Strategic Impact				Deliverability			
	Impact on Energy and Carbon Intensity	Impact on Sustain-ability	Effects on UK's Competitive Advantage	Impact on Energy Security	Impact on UK's Techno-logical capabilities	UK Competitive Position	Development Status and Technological Potential	Barriers to commercial use
CO2 Separation	Very High	High	High	High	Moderate	Favourable	Mature	High
Geologic Storage of Carbon Dioxide	Very High	High	Low	High	High	Strong	Varies with process	Moderate

4.5 Social and Economic Research

The Trust will need to support social and economic research on societal responses to climate change, including social and economic influences on technology development. The reasons for this were raised during the stakeholder interviews with both the business and the research communities:

(1) *Public perceptions as to the environmental effects, costs and risks of new technologies*. These exert a large influence over the direction of technology development, and are often a source of opposition, as we have seen in the case of nuclear power, various transport projects and onshore wind projects, to cite a few examples. However, public perceptions are also a positive force for screening promising options. Social surveys consistently show that the public places a positive value on environmentally acceptable approaches, and on investments to improve health and safety, which are often not captured in market signals. The main examples so far have been in the protection of natural resources, wildlife and national heritage, but the approach could be extended to energy demand and supply technologies and transport. Would the public support the extra costs of developing offshore wind and

wave energy for example, if it will eliminate concerns over environmental intrusion in onshore and coastal projects? What will be the reaction to the use of hydrogen as a fuel, or to the emergence of distributed generation? The comment was made that when the Trust is committing to developing a technological option, it is necessary to look at its social and economic desirability and issues concerning the public's likely reactions to it.

(2) *Changing lifestyles and patterns of growth and development.* The range of possibilities ahead is appreciable. The following are examples of social and economic change that will influence the directions of technology development and the level of greenhouse gas emissions:

- The balance of public and private transport;
- The choice of transport modes;
- Congestion management;
- The emergence of traffic-free zones;
- Leisure-income trade-offs and the nature of leisure;
- Changing private and public values and consumption patterns;
- Information technology and the possibilities for working and shopping from home;
- Increased integration between transport and energy systems
- Changing demographic patterns
- Raising awareness of the potential use of more efficient technologies and practices.

(3) *The search for a structure of policies at the national and international levels.* Policies will have an appreciable influence on the directions of technology development through the opportunities they create for invention and innovation, the through their influence on investment. The creation of the Trust itself is a consequence of a policy, the Climate Change Levy, and of public and industrial reactions to it. Policies are far from settled at the national level, even less at the international level. In the UK as in other OECD countries present policies include a complex mix of

- Short- and long-term targets;
- Tax incentives;
- Green certificates;
- Premium prices for low carbon energy forms;
- Rebates for efficiency or emissions reduction;
- Product certifications and standards;
- Voluntary arrangements;
- RD&D;
- Tradable permits;
- Environmental regulation;
- Regulation in the energy, transport and building markets;
- Education and training;
- Raising awareness of the potential use of more efficient technologies and practices.
- The development of the country's research capacity; and

- Co-operative arrangements and international agreements between countries.

Interdisciplinary research at the interface of the social sciences and engineering is a low budget item relative to that required for technology development. Yet coupled with good outreach programmes such research would greatly influence the UK's capacity to respond to climate change, not least in the development of new technologies, and to exert international leadership on climate change policies. Table 4-12 provides an assessment, using similar criteria to those used in the technology assessments.

Table 4-12 Assessment of the Role of Social and Economic Research

Deliverability:		
UK position	Strong.	Excellent economic and social science base in the country. Significant contribution to research on national and international policies.
Potential of the research	Important in the long-term and the short-term	Capable of exerting large effect on technology development and use. Interdisciplinary approaches between the social, engineering and physical sciences need to be developed.
Uncertainties and risks	Not large	Relevance would be enhanced by core-funded research. Necessary to have good outreach programmes, and accountability to stakeholders. Funding would need to include support for either dissemination or implementation studies. This could also help to increase the public acceptability of new technologies.
Strategic Impact:		
On sustainability	Very high	Clear and well thought through policies are fundamental for success at the national and international levels
Energy Security	High	Research would facilitate emergence of technologies and practices using UK renewable energy resources.
Impact on UK's Technological Capabilities	High	Fundamental. See text and 3rd row above.

One stakeholder interviewed summed up the argument as follows. That what is needed is an approach to defining RD&D priorities based on three principles: (a) a 'partnership approach' between industrial and academic researchers to improve scope, relevance and application of results; (b) inter-disciplinarity, both within the social sciences and between the social sciences, engineering and the physical sciences; (c) core funding, such that a long-term research capacity can be developed in the UK in the relevant fields.

4.6 Recommendations: Thematic Priorities and Ground rules for Building a Portfolio

The thematic priorities for RD&D on technologies and practices fall roughly into two groups:

1. Those with good medium term prospects, capable of yielding continual, but incremental reductions of carbon emissions in one or both of two ways: (a) through improvements in energy efficiency, and (b) reductions in carbon emitted per unit of energy use. Included in these are the following technologies and practices discussed above:

- Energy efficiency improvements in buildings, industry, transport and electricity supply from fossil fuels;
- Renewable energy from biomass—of biomass wastes in particular—and onshore and coastal wind;
- Fossil fuel gasification with carbon separation and sequestration;
- Micro-turbines for distributed generation and heat (distributed CHP).

2. Those with good long-term prospects of yielding very large reductions of emissions, and even of a complete transition to a zero carbon economy. They are sometimes described as ‘disruptive’ or ‘transforming’ technologies:

- Solar energy and the full range of offshore renewable energy resources;
- Storage systems for stationary applications and transport, to solve the economic problem posed by the intermittency of renewable energy;
- Hydrogen production, distribution and storage technologies;
- Fuel cells for transport, for distributed generation and heat (distributed CHP).

The main conclusion from the above analysis, which we believe was shared by the majority of those we met in the stakeholder interviews, was that the Trust should not focus exclusively on one of these groups or the other, but have a broadly balanced portfolio that includes both. The incremental benefits arising from the first will be important, and with continued innovation will accumulate appreciably over a long time horizon—as the scenarios of the Report of the Royal Commission on Environmental Pollution has shown (see Chapters 2 and 3). But by themselves, there are distinct limits to what they can accomplish. They are *not* a long-term solution to the climate change problem. Hence they need to be accompanied by research on the kinds of technologies identified in the second group.

We have also concluded that the RD&D portfolio should not be exclusively focused on technology development. The stakeholders we interviewed also shared this view. The reason is that the development and use of the technologies that emerge out of the RD&D programme will be dependent upon future social and economic developments in complex ways, not least on future policies, on which we comment further in Chapters 5 and 6. There is a need to combine social and economic research with technology assessment studies, with a strong emphasis on inter-disciplinarity.

The preceding analysis did not attempt to specify the precise RD&D projects that the Trust should support, but concentrated on thematic priorities. Project identification can and should be encouraged and facilitated by the Trust, but the projects themselves, and the ideas on which they are based, will be those of literally thousands of researchers and project developers in the country, not those of the Trust. The question thus needs to be addressed, what criteria should the Trust use for the approval of its projects?

There is no simple answer, such as the risk-weighted social rate of return to investments, in which the social return allows for the estimated external benefits of the project’s mitigating climate change. The uncertainties are too large, and we are not even close to estimating the social costs of climate change, in the UK or elsewhere. Second, innovation is a highly non-linear stochastic process, in which seemingly small discoveries can lead to large and far-reaching changes; RD&D projects (especially those in the second group noted above) frequently have a strategic value, in the sense of opening pathways to a low carbon future, that go beyond the particular step they represent in and of themselves.

A better approach is to follow a number of ground rules, which are suggested by both the preceding analysis and by the people met in the stakeholder interviews:

1) Assess whether projects are consistent with the thematic priorities.
2) Use a mix of funding rules, avoiding rigidities in the matter of co-finance:

- Core funding for basic research;
- Higher leverage of private capital for the near-term, lower-risk RD&D projects;
- Lower leverage for longer-term, higher risk projects. Technologies in this category tend to be higher up their cost curves and often merit proportionally more financial support.

3) Use the peer-review process for the majority, say 80% of projects, but leave room for innovative ideas that may challenge the peer review process. Experience suggests that it is the low-probability, high-risk ideas, frequently opposed by the 'consensus' of peer reviewers, which bring about paradigm shifts.[11] Peer reviews are good for securing high quality RD&D following a familiar path, but for the same reason can often be blinkered and stifle innovation.
4) Assess cost trends, and identify cost goals for the technologies to be developed.
5) Support the portfolio development through social and environmental risk assessments of the various categories of technologies to be financed.

Partnerships with industry are also a means of course of giving the investments a near-market test, if there is a sharing of financial risks between industry and government.

[11] An observation made to us by Ian Harvey, Chief Executive of British Technology Group.

5 INTERACTION OF THE TRUST'S RD&D STRATEGY WITH RELATED POLICY DEVELOPMENTS

5.1 Links between the Trust's Activities and Other UK Policies

The Carbon Trust will be only one of a number of agencies whose activities will influence the development and take up of low carbon technologies. Thus, the Trust needs to put its RD&D strategy in a wider context and to consider the nature of its interaction with those other agencies. The Trust will also work within a complex and evolving policy and regulatory framework, based on liberalised markets. In developing its RD&D strategy the Trust need to take account of the influence of

- regulatory policies;
- economic instruments of environmental policy; and
- innovation policies, including but not only RD&D.

The importance policies to provide direct support for environmental innovation is becoming recognised. The case was outlined in a recent report[12], drawing out conclusions from a series of Workshops held at Imperial College, with participants from industry, academia and the policy-making community. This is discussed in the next section.

Several suggestions on policy also arose in the stakeholder interviews:

1) *Contribution to the policy-making process*. The Trust will have the opportunity to rapidly accumulate knowledge and experience in the development of low carbon technologies, and in associated social and economic issues associated with the 'barriers' to their use. It will be important for the Trust to build the institutional capacity to be able to positively apply this knowledge and experience to engage with UK policy making.
2) *Working with other stakeholders*. The Trust will need to work with stakeholders, including government departments, devolved administrations, environmental NGOs, green technology companies, major energy providers, Trades Unions and the research community. In one stakeholder interview, the ESRC representative noted ways for achieving successful deliberative and interactive processes for involving stakeholders have been identified (Stirling and Mayer, 1999). Others stressed the need for the Carbon Trust to work closely with the Energy Saving Trust (EST), which has developed support mechanisms in the domestic energy efficiency and transport sectors.
3) *Complementarity with other RD&D funding*. The Trust will need to ensure that the RD&D it supports complements that provided by other programmes, including that by the EPSRC and ESRC under the successor to the Renewable and New Energy Technologies programme, the Sustainable Technologies Initiative, and the DTI's New and Renewable Energy Programme.

[12] ICCEPT (2001), *Innovation and the Environment: Challenges and Policy Options for the UK*

4) *Capacity development*. Several stakeholders said there was a role for the Trust in the development of the research capacity and skills base in the country with respect to the new low carbon technologies and practices.

5) *Contribution to a stable policy and funding environment*. The importance of a stable policy and funding environment was emphasised by industry representatives. Because of the long time scales involved in the development of many new technologies and practices, the expectation of continuing support for movement towards a low carbon economy is recognised to be vital.

5.2 The context of RD&D within innovation policy

The establishment of the Carbon Trust has provided the UK with an unprecedented opportunity to build its research capacity, and to develop and demonstrate the products of its research, in response to the problems posed by climate change. Public support for energy-related RD&D in the UK fell eight-fold from £350 million per year in the late 1980s to £44 million in 1998, largely on the grounds that, following the privatisation of the gas and electricity industries, the onus for technology development had shifted to the private sector. (The decline of R&D in nuclear power was another factor.) We are now seeing a recovery of RD&D policies, and a new approach.

The new approach is an appreciable departure from the old linear model of 'R&D in = innovation out'. There is now far more emphasis on continual feedback between the various phases of technology development from basic research through to commercialisation, on the discoveries and improvements arising from investment and operating experience (learning-by-doing), and on creating networks for innovation (see POST report on clean technologies). This involves more consultation between government, industry, the research community and the public when priorities are being identified, more collaboration between the public and private sector in the execution of research, and more post evaluation of experience gained.

The magnitude of the task of addressing the climate change problem is one reason for the resuscitation of energy-related RD&D policies. But equally important is the recognition that direct support for innovation will be required to develop low carbon technologies and practices. The 'standard' instruments of environmental policy—environmental taxes, tradable permits and regulations—though necessary, are inherently limited in promoting innovation.

The rationale for supporting innovation policies is that they complement the standard instruments of environmental policy by:

a) Creating options and reducing risks. The uncertainties and risks of responding to climate change are considerable, and there is a value (an 'option value') to policies that create options or bring them forward in time.

b) Improving the elasticity of response to environmental policies. In the short-term, the costs of the alternative technologies and options —with the important exceptions of much-discussed 'win-win' options in energy efficiency—can be extremely high and the near-term demand and supply responses inelastic. In the short term environmental taxes raise revenues (and hackles), while leading to little environmental improvement. Accelerating the development of the non-carbon options will enable substitution to take place earlier, and at a lower cost.

c) Giving rise to positive economic externalities—by reducing costs and making options available to future generations of investors.

These policies could also facilitate the brokering of international agreements. For example, it is argued that the reason that the Montreal Protocol on limiting ozone-depleting emissions was readily accepted internationally in 1990 was that industry had identified low cost alternatives to CFCs, which made substitution away from them less difficult. It can be anticipated that, *if* RD&D and the supporting policies for innovation are similarly successful in developing low carbon technologies at acceptable cost, then future agreements on climate change policies will be more easily reached and implemented.

There are a number of policy options available, including long-term targets and obligations, tax incentives and credits for innovation, public procurement programmes, and targeted strategic support for technologies and capacity building, as well as support for RD&D. *All* OECD member countries, and several developing countries, including China, India and Brazil, now have policies to support technology development directly. This includes the US, which, despite its recent apparent withdrawal from the Kyoto Agreement, has strong policies to support the development of low-carbon technologies directly – with Federal commitments exceeding $1 billion per year by the late 1990s. UK energy and environment policies are now starting to apply such policy options, as described below.

5.3 UK energy and environmental policies

The Trust will operate within a complex and evolving policy framework, which aims to meet energy supply and environmental goals within a liberalised market.

UK energy and environment policy (DTI, 2000) has as its aims:
- to provide secure, diverse, sustainable and competitive energy supplies;
- to assist the UK to meet national and international targets for the reduction of emissions, including greenhouse gases.

In addition, the government's renewable energy policy aims:
- to stimulate the development of new technologies necessary to provide the basis for continuing growth of the contribution from renewables into the longer term;
- to assist the UK renewables industry to become competitive in home and export markets and, in doing so, provide employment;
- to make a contribution to rural development.

The UK Climate Change Programme (DETR, 2000) sets out the measures to meet and exceed the UK's target under the Kyoto Protocol of reducing greenhouse gas emissions by 12.5% below 1990 levels by 2008-2012, and work towards the UK Government's goal of a 20% reduction in CO_2 emissions from 1990 levels by 2010. These measures include the package of the Climate Change Levy on the use of energy by business and the public sector, together with exemptions for renewables and CHP. The Government has completed agreements with around 40 energy intensive industry sectors to meet specified energy efficiency targets, in return for an 80% reduction on the Climate Change Levy. These sector targets will result, by 2010, in a saving of 2.5 MtC per year, compared to the Business as Usual scenario (ETSU, 2001). A further 2.5 MtC is expected to be saved by the Renewables Obligation on electricity suppliers, which will require 10% of electricity to be generated from renewable sources by 2010, subject to the cost to consumers being acceptable. The major saving in the transport sector, of 4 MtC, is expected as a result of the voluntary agreement at EU-level with auto manufacturers to reduce the average CO_2 emissions from the fleet by 2008 to 140 g/km (DGXI, 1998).

Such policies will exert a large influence on the economic returns to investment in low-carbon RD&D technologies, and therefore on what activities the Trust will want to support, as will a range of other policies in the energy and other sectors that are continually under review. For example, the Performance and Innovation Unit (PIU) in the Cabinet Office is currently undertaking a study of the contribution of energy productivity and renewable energy to achieving sustainable economic growth within the context of using natural resources more efficiently. The study will look at strategies for increasing energy productivity and the use of renewable energy in the UK both up to 2010 and out to 2050.

The PIU study will also set out how the £100million for the next three years announced in the Prime Minister's environment speech at Chatham House on 6 March will be used to support the development of a range of renewable technologies. This will form part of the Government's support for renewables of £260 million over the next three years (DTI 2001), including:

- £50 million National Lottery money mainly for capital grants for offshore wind and energy crops;
- DTI's £55.5 million for the Government's enhanced renewable energy research and development programme;
- DTI's £39 million support for capital grants for offshore wind; and
- MAFF's £12 million in grants for planting energy crops.

Another element of UK policy is the *Enhanced Capital Allowances (ECA)* scheme, which will be administered by the Carbon Trust. This will provide 100% first year capital allowances for approved energy saving investments for businesses on: Combined Heat and Power; Boilers; Refrigeration; Motors; Variable speed drives; Lighting; Pipework insulation; and Thermal screens. Up to £100 million will be available in 2001-02 under this scheme. A key role for the Trust will be to build on and extend the list of approved energy efficiency and low carbon technologies available for support under this scheme.

5.4 International Policies and Collaboration

Some technologies can only be effectively developed at an international scale, while there is also a potential opportunity for the Trust to play an appropriate part in the UK's exercise of international leadership, especially in relation to the developing world. There is already an elaborate apparatus for the development of international policies on climate change. It is derived from the UN Framework Convention on Climate Change (FCCC), which has been described as "the most ambitious effort ever to limit the human population's impact on the environment."[13]

The FCCC has two aspects. The *first* concerns the process of negotiations leading to the Kyoto Protocol and the subsequent meetings of the Conference of the Parties, which agreed emissions reduction targets for industrialised countries and attempted to set ground rules for the implementation mechanisms (CDM, Joint Implementation and Emissions Trading). Although the US has recently announced that it will not ratify the Kyoto Agreement, this arises from disagreements over targets, costs and the participation of developing countries: it is *not* a decision to pull out of the FCCC.

The *second* aspect is the *Global Environment Facility*, which is the financing arm of the FCCC. It was established on a pilot basis in 1990, and finances *proven* low carbon technologies and practices in developing countries. It is a grant facility, intended to meet the incremental costs of using such technologies and practices relative to the fossil fuel alternative they displace. It uses the grant to lever considerable private and public capital resources to the projects. As of June 30, 2000, it had approved $7.1 billion of investments in 272 projects (Table 5.1):

Table 5-1 GEF Climate Change Portfolio by Type of Project, as of June 30, 2000

Type of Project	No. of Projects	GEF funds, $ millions	Total Project Cost, $millions
Enabling activities (field studies, project preparation and other)	142	82	89
Energy Efficiency	40	251	1727
Renewable Energy and Low carbon Projects:			
• Near-commercial uses[a/]	52	395	3948
• entailing incremental costs	10	200	684
Sustainable Transport[b/]	3	15	26
Short-term measures [c/]	25	137	628
Totals	272	1081	7102

[13] Skea in Chapter 19 of Steve Sorrell and Jim Skea (1999), *Pollution for Sale: Emissions Trading and Joint Implementation*. Cheltenham UK: Edward Elgar.

Source: Draft report on *The GEF Climate Change Program Study* by Eric Martinot and Ramesh Ramankutty of the GEF Sectretariat, March 30, 2001.
a/ Renewable energy and other projects such as use of landfill gas and coal bed methane leakage that are thought to be economically justified but require efforts to address 'market barriers'.
b/ This is a relatively new operational programme, hence the still-low number of activities.
c/ Low cost near-term options for reducing emissions that are not covered by the preceding categories.

The portfolio of projects for which finance has been approved over the first 10 years of the GEF is very diverse. It includes the full range of renewable energy projects, such as photovoltaics for over 500,000 solar home systems, health clinics, water pumping and other; thermal solar for water heating and power generation; methane recovery from coal beds and landfill gas; biomass for power generation; wind; micro-hydro; fuel cells for transport and studies of fuel cells for power generation; a very wide range of energy efficiency activities and projects; and a large number of project and policy development (or 'enabling') studies.

The main omission at the international level is any facility that will foster investments that would shift the 'technology frontier' in low carbon technologies in developing countries—in contrast to the many investments in fossil and, in some countries, nuclear energy. Yet several categories of renewable energy project have greater potential in developing countries than in most industrial countries, and there are opportunities for 'leapfrogging'.[14] For example, solar energy is five or more times economically more attractive in developing countries on account of the higher solar insolations and the better match between energy demands and the incident solar energy. The energy markets are also potentially huge: the electricity demands increase by more than 70,000 MW per year, which is more than the size of the UK electricity system.

Thus the Trust has a novel and potentially important role to play in fostering international co-operation in technology development. This is likely to be crucial to ensuring the continuing development of international policies on climate change.

Amongst the options that the Trust should explore are:

(a) Setting up a Forum for international exchange of information on current technological developments, with a view to:

(b) Establishing a consortium or facility to support RD&D for advanced low carbon technologies which would push forward the 'technological frontier'; and

(c) Exploring the ways in which such an initiative would link consistently with other mechanisms, such as the Clean Development Mechanism (CDM), under the UNFCCC framework.

[14] See the US President's Committee of Advisers on Science and Technology (1999). *Powerful Partnerships: The Federal Role in International Co-operation on Energy Innovation*. Washington DC. President's Office

5.5 Conclusions

The importance of policies to support environmental innovation directly is now being recognised. The Trust will need to work with other stakeholders, particularly with other bodies supporting technology development and take up, including the Research Councils and the Energy Saving Trust. The Trust will also need to build up its own capacity to contribute to the continuing development of policy making.

The UK Climate Change Programme sets out a number of measures to meet current targets up to 2010, which, if successfully implemented, will enhance the UK's position as an international leader in carbon emissions reductions. The Trust can build on this position to play a role in fostering international co-operation in technology development. This would fill a conspicuous gap on current international policies on climate change.

6 SOCIAL AND ECONOMIC ASPECTS: MARKET OPPORTUNITIES, BARRIERS AND RESPONSE

6.1 Market Opportunities

Given the size of the energy markets in the UK the gradual substitution of low carbon for carbon-intensive technologies and practices is bound to give rise to major earnings opportunities. This is even more so at the international level, where energy markets are 40 times larger and, with growth in the developing countries, are set to be 100 or more times larger in 50 years' time. Table 6.1 provides some estimates:

Table 6-1 Prospective Primary Energy and Electricity Generating Capacity Requirements in the UK and Globally

	Today	**c 2050**
Primary Energy (Mt.o.e):		
▪ UK	230	230
▪ World	8,500	15,000-25,000
Electricity (GW installed):		
▪ UK	65	65
▪ World	≈3,000	6,000-10,000

Notes: The UK projections follow the energy demand scenarios in the report of the Royal Commission on Environmental Pollution. The Global projections correspond to the middle and high growth cases of the World Energy Assessment Report.

This is to understate the possibilities ahead, since the links between energy production and use to the manufacturing, transport, service, and construction industries are deep and pervasive. If, for example, the fuel cell succeeds, it will affect virtually every aspect of the vehicle design and manufacturing, of the infrastructure needed to provide fuels, and of the world's electricity supply industry. The 'intermediate consumption' by the energy industries alone is very large.[15]

However, it is insufficient to rest the case by noting the prospective size of the market. There are barriers to *market development*, arising from uncertainties about costs and future policies, and barriers to *market entry*, in both cases arising from uncertainties and social and economic factors. These are discussed below. The key point for the Trust when developing its portfolio, again emphasised by several stakeholders we interviewed, is that it is necessary to look at the markets for the technologies and how they are functioning, as well as the technologies themselves.

[15] The National Accounts show that in 1998, the input of intermediate goods to the electricity, gas, mining and water industries aggregated to £50 billion, which was more than three times final consumption expenditures by the industries' consumers.

6.2 Cost Thresholds, Uncertainties and Risks

Uncertainties about the financial returns to investments in the technologies discussed in Section 4 are appreciable. While there is significant investment taking place, industry must still face the questions, what if costs do not decline by as much as expected—will policies still support their use? Suppose ongoing research eventually finds that the dangers of climate change have been exaggerated—will policies be relaxed, and will the technologies then still be needed?

Estimates show that the rates of decline of cost with investment vary over a wide range. The following are estimates compiled by McDonald and Schrattenholzer for selected technologies. The learning rate is the percentage reduction of costs for each doubling of the cumulative volume of production:

Table 6-2 Learning Rates for Selected Energy Technologies

Technology (and source of estimate)	**Period**	**Learning Rate, %**
Wind:		
• OECD	1981-95	17
• US	1985-94	32
• California	1980-94	18
• Denmark	1990-94	8
Solar PV:		
• EU	1985-95	32
• World	1976-92	18
Ethanol (Brazil)	1979-95	20
Electrolytic Hydrogen from renewables (engineering studies)	--	18
Compact Florescent Lamps (US)	1992-98	16
Gas Turbine Combined Cycle Power Plants:		
• OECD	1984-94	34
• EU	n.g.	4
Gas Pipelines:		
• Onshore	1984-97	4
• Offshore	1984-97	24
Oil Extraction from the North Sea	n.g.	25
Coal for Electric Utilities	1948-69	25
Nuclear Power (OECD)	1975-93	6
Electric Power Production	1926-70	35

Source: Except for electrolytic hydrogen, which is based on Ogden's review in the 1999 *Annual Review of Energy and the Environment*, the estimates are quoted from A. McDonald and L. Shreattenholzer (2001), "Learning Rates for Energy Technologies", Energy Policy 29: 255-261, who give estimates for several other technologies and from other sources.
n.g = not given.

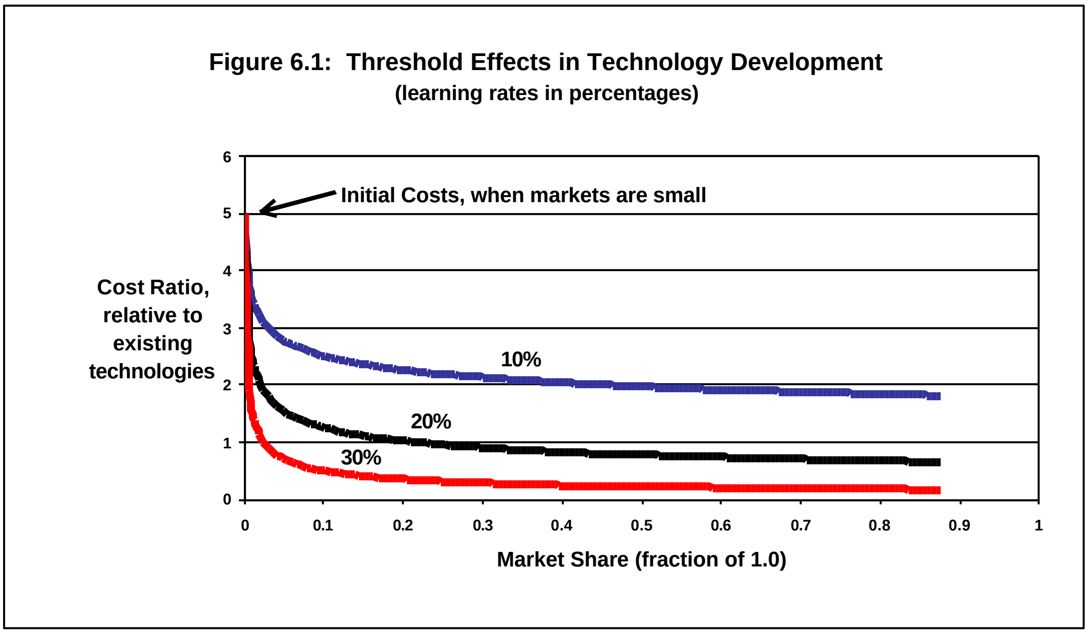
These estimates show that:

- There is much historical evidence in the energy industry to show that costs decline appreciably, and over long periods, with innovation, investment and operating experience.
- The effects are notably strong for—but are not confined—to renewable energy.

- Even for particular technologies, on which substantial experience has already been gained, the estimates show a wide range.

The 'learning-by-doing' effects are exceedingly important, however, in the early phases of a technology's development. When it occupies (say) around 0.001% to 0.01% of the energy market, even a 100-fold expansion still leaves it occupying only 0.1% to 1% of the market; but experience accumulates rapidly in this period, and costs may decline several-fold. In contrast, when it occupies a larger share, the cost reductions are still significant (as for example with gas-turbine power plant) but are small in comparison. In other words, there can be a phase of rapid catch-up. Figure 6.1, based on the above data illustrates the point, and serves to show the extent of the thresholds and non-linearities that exist in the early phases.

Figure 6-1 Threshold Effects in Technology Development



The high initial costs—coupled with the uncertainties as to how far they might decline, and whether climate change policies will support them when developed—present an appreciable barrier to entry. These are reasons (a) why support for RD&D and risk-sharing arrangements between the public and private sectors are needed in the early phases of development, and (b) why such policies need to be complemented by market development policies once the RD&D phase is over. (See section 6.4.)

6.3 Economic Barriers to the Growth in Demand for New Technologies

Significant issues identified in the research literature are:

1. *The problem of split incentives*. This occurs whenever different actors would experience the costs and benefits of an investment. It is often known as the *tenant-*

landlord problem, in which the landlord is responsible for the fixtures and fittings of a building, but the tenant pays the energy bills. The landlord has no incentive to pay the costs of installing energy efficient as the benefits of lower energy bills would accrue to the tenant. Research by the Association for the Conservation of Energy (ACE) (Scrase 2001) has shown that this is also a significant barrier to the take-up of energy efficiency measures in the commercial service sector, where, for example, up to 90% of offices are occupied by a tenant rather than the owner.

2. *Adverse selection*. This refers to a case when asymmetric information between the seller and the purchaser results in good products being driven out of the market by poorer products. For example, because developers do not factor running costs into the prices of buildings, more energy efficient buildings with higher up-front but lower running costs are often undercut by developers selling less efficient buildings.

3. *Access to capital*. The lack of access to capital is a barrier, for example to managers subject to direct capital constraints. Within commercial companies, capital is often rationed or less available for small investments. Organisations will impose much higher rates of return on small investments partly to offset transaction costs. This can be compounded by the *principal-agent* problem, in which the principal (say the manager in a firm) who has to make investment decisions has less information about the merits of the proposed projects than the agent (say the energy manager) who proposes the projects.

4. *Transaction costs*. The costs of finding information, negotiating agreements and contracts and organising purchasing agreements are all examples of transaction costs that are usually excluded from calculations of cost-effectiveness. Yet they usually amount to less than 10% of the potential cost savings.

As an example, an analysis of barriers to energy efficiency in public and private organisations, together with how those barriers may be overcome, has recently been undertaken by a research team lead by SPRU at the University of Sussex (Sorrell et al., 2000), and in a briefing paper on energy productivity for the PIU study on renewable energy and resource productivity (Chapman and Eyre 2001). Sorrell et al. found that the major barriers to the take-up of energy efficiency measures were a lack of motivation coupled with competing demands on the times of decision-makers. These arose from constraints on staff time (the hidden costs of staff overheads) and a generally low priority given to energy efficiency within the companies budgeting procedures. Many businesses do not routinely monitor how much energy they use.

6.4 The Consultation Process and Public Perceptions—a Positive Force

Company and public perceptions of the environmental effects, costs and risks of new technologies exert a large influence over the direction of technology development, and are often a source of opposition, as we have seen in the case of nuclear power, various transport projects and onshore wind projects, to cite a few examples. However, perceptions are also a positive force for screening promising options.

Beliefs depend on information acquisition, which includes the influences of the media, marketing campaigns, social interactions, and personal experiences of products or things that can be in any way associated with the technology. Acquisition will be affected by the firm's (or individual's) demand or perceived value of learning about the technology and by the overall market for information, including the level of production and supply. Beliefs also depend on how information is used. Its use will be influenced by the quantity of information acquired, the means of acquiring it, the 'dramatic content', the credibility of the source, and the ability to understand it and assess its accuracy. Finally, beliefs about new products fit within a firm (or an individual's) broader value system, and the costs and benefits of holding on to the beliefs. The value system a firm (or an individual) forms is influenced by the economic, social, political, cultural, intellectual, spiritual and historical context within which he or she makes decisions. Thus a society that reminds its companies and citizens of the association between carbon intensive products and climate change will be more likely to place a value on low-carbon technology. And, tied-in with this is the need to reduce the perceived risks of low-carbon technology.

Social surveys consistently show that the public values environmentally acceptable approaches, and investments to improve health and safety, to an extent that is not fully captured in market signals. Most surveys have been undertaken into the value of protecting natural resources, wildlife and national heritage, but the approach could be extended to energy demand and supply technologies and transport. Would the public support the extra costs of developing offshore wind and wave energy, for example, if it will eliminate concerns over environmental intrusion in onshore and coastal projects? What will be the reaction to the use of hydrogen as a fuel? Are projects needed to demonstrate its safety? More generally, what are the key social, environmental and safety attributes of low-carbon technologies? The Trust could usefully promote the further exploration of these sorts of questions (in support of this recommendation, during the stakeholder interviews, the comment was made that before the Trust committed to developing a technological option, it would need to assess its social and economic desirability, and the public's likely reactions to it). The Trust might also draw on the findings of such studies to scope support to demonstration projects that address positive or negative aspects of particular technologies.

6.5 RD&D and Market Development Policies

Thus recent research supports the idea of policies (now under development) to foster the market application of low carbon technologies and practices themselves. 'Getting prices right' is of course one step, particularly, in the present case, through environmental taxation and regulation. But the social and economic literature has gone beyond this, and suggested a number of further measures.

On energy efficiency, for example, we now have the following (Chapman and Eyre, 2001):

- *Regulations* - e.g. the revised Building Regulations imposing energy efficiency standards on buildings.

- *Negotiated agreements* - e.g. the agreements negotiated with energy intensive sectors for specified improvements in energy efficiency in return for an 80% discount on their Climate Change Levy payments.
- *Taxation* - e.g. the Climate Change Levy on the business use of energy will stimulate more attention being paid to the potential for energy saving investments.
- *Grants* - e.g. the Energy Saving Trust offers grants to homeowners for installing loft insulation.
- *Tax incentives* - e.g. the Enhanced Capital Allowances for investments in specified energy efficient technologies, which will be administered by the Carbon Trust.
- *Information and education* - e.g. energy labels on products and disseminating best practice. To overcome the above barriers, information needs to be well targeted to encourage the take-up of improved technologies and practices.

The Performance and Innovation Unit in the Cabinet Office is currently revisiting renewable energy policies. The general principle of complementing RD&D by tax and regulatory incentives that reflect the positive externalities of innovation is now generally accepted. The Imperial College Workshop Report (February 2001) on *Innovation and the Environment: options and challenges for UK policies,* in which several government departments and companies participated, summarised the policy options.

6.6 Conclusions

The substitution of low carbon technologies and practices will give rise to major earnings opportunities in both UK and international energy markets. However, there are barriers to market development, arising from thresholds, social and economic factors, and uncertainties about costs and future policies. The key point for the Trust is that it is necessary to understand the markets for the technologies as well as the technologies themselves. Thresholds and non-linearities often exist in the early phases of a technology's development. High initial costs, coupled with uncertainties about their future decline and about whether climate change policies will support them when developed, can present an appreciable entry barrier. This is why support for RD&D and risk-sharing arrangements between the public and private sectors are important in the early phases of development, and why such policies may need to be complemented by market development policies once the RD&D phase is over. The Trust should pay particular attention to enhancing understanding of the potential for cost declines and of the factors and interventions that might promote or retard them.

7 CONCLUSIONS AND RECOMMENDATIONS

There are a large number of studies by industry and the research community which show that a low carbon future is technologically and economically feasible, both for the UK and the world economy.

Furthermore, *all scenarios of a low carbon future are scenarios of economic success*, in the sense that economic prosperity is eventually achieved on a broad basis, in both developing and industrial countries. The reasons for this conclusion are that:

- Energy demands could eventually be met by non-carbon alternatives to fossil fuels. The transition would take a long time—perhaps one-half to the whole of this century—and fossil fuels are bound to be the most important source of energy for several decades, but the possibility is now no longer in question.

- There are significant opportunities being opened up by technical progress in low and non-carbon technologies. The long-term costs of the transition may (a) raise or (b) lower the real costs of energy somewhat, or even leave energy costs virtually unchanged. The uncertainties are still too large. However, the scope for cost reductions through research and innovation is appreciable, and the transition would not be disruptive to economic growth; growth may even be higher. Furthermore:

- Gains in efficiency, particularly in transport technologies and practices, and in energy use in buildings, commerce and industry would themselves be sources of economic improvement.

- Scenarios of economic success are associated with greater economic choice and greater innovation.

Thus, a low carbon UK economy would be more prosperous than it is today. On current growth trends per capita incomes would rise from today's level of around £15,000 to £50,000 by the middle of the century, and the UK would be well on course, if this becomes necessary, to reducing carbon emissions to whatever level is required.

As regards technological priorities for RD&D, we have recommended a broadly-based portfolio on technologies that can be roughly classified into two groups:

1. Those with good medium term prospects, capable of yielding continual, but *incremental* reductions of carbon emissions in one or both of two ways: (a) improvements in energy efficiency, and (b) reductions in carbon emitted per unit of energy use. Included in these are:

- Energy efficiency improvements in buildings, industry, transport and electricity supply from fossil fuels.
- Renewable energy from biomass and onshore and coastal wind.
- Fossil fuel gasification with carbon separation and sequestration.

- Micro-turbines for distributed generation and heat (distributed CHP).

2. Those with good long-term prospects of yielding very large reductions of emissions, and even of a complete transition to a zero carbon economy. They are sometimes described as *disruptive* or *transforming* technologies:

- Solar energy and the full range of offshore renewable energy resources, supported by research on:
- Storage systems for stationary applications and transport, to solve the economic problem posed by the intermittency of renewable energy. Related to this:
- Hydrogen production, distribution and storage technologies.
- Fuel cells for transport, for distributed generation and heat (distributed CHP).

The main conclusion from the above analysis, which we believe was shared by the majority of those we met in the stakeholder interviews, was that the Trust should not focus exclusively on one of these groups or the other, but have a broadly balanced portfolio that includes both. In Chapter 4 we suggested some ground rules for the development of the RD&D portfolio.

We have also recommended that the Trust should support research on the social and economic issues that will be encountered in the transition to a low carbon economy. Social and economic conditions, which include public perceptions and reactions to new technologies, and the policy environment, will together define the enabling conditions for technology development and use, and the course of technology development itself.

On the policy side, we have outlined the economic rationale for the Trust's support for RD&D. This is that it will help the UK, and its international companies engaged in the energy business, to widen the range of technological options and reduce the costs of low carbon technologies. Reducing costs will, in turn, facilitate market development under the incentives provided by policies toward climate change.

At the international level there is a novel and important role for the Trust, which would be to foster international co-operation in technology development. There is a gap in current international policies (as several stakeholders also noted), which concentrate heavily on emissions targets and little on the development of the technologies and practices required for meeting targets. The Trust should consider setting up a Forum for international exchange of information on current technological developments, with a view to establishing a consortium or facility to support RD&D for advanced low carbon technologies that would push forward the 'technological frontier'.

This would unquestionably be an action of enlightened self-interest, as the economic opportunities are immense. The world energy markets are set to double or triple in the coming decades, and perhaps 8 million MW of new generating capacity and 15-20 billion tonnes of oil equivalent energy will be needed—more than 100 times the UK's markets. Many stakeholders, including enlightened elements of the oil industry, believe that this could be met by low carbon technologies of the kind reviewed in this report.

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APPENDIX I: FURTHER DEFINITIONS OF SCREENING FACTORS.

Strategic Impact– a measure of the impact that the intervention could have on the strategic aims of the Carbon Trust, as reflected by the following factors

Energy Efficiency and Carbon Intensity	• Provides for a significant increase/decrease in energy/carbon intensity – **High**>30% in Sector, **Moderate** 15-30%, **Low** <10%
Energy Sustainability	• Moves UK towards energy sustainability - **High** – makes a significant contribution through reduced energy dependence and substitution by renewable primary energy sources and is a key step on an evolving pathway to zero emissions. **Moderate** – significant impact in 2 out of three areas above or more modest impact in all three. **Low** - significant impact in only 1of 3 areas
Technology Competitive Position	• Embodies technologies that have enduring competitive advantage and will drive new business opportunities for UK – **High** – embodies technologies that have the potential to change the entire basis of competition and not yet embodied in products or processes. **Moderate** – embodies technologies that currently dominant in their sector and embodied in products and processes that are differentiated by leading companies or technologies that have the potential to become key in niche applications. **Low** embodies basic technologies that are generally widespread and shared.
UK Energy Security	• Maintains or improves UK's energy security. **High** - both significantly reduces primary energy dependence and significantly increases diversity of supply. **Moderate** - offers modest improvements in both factors or significantly affects only one. **Low** – affects only one factor in a modest way.
UK Technological Capabilities	• Broadens and deepens UK technological capabilities. **High** – UK already significant player in the development, supply and application of these all related technologies **Moderate** – UK a strong /modest player in a limited/significant part of the technology supply chain. **Low**- UK only has a limited involvement in the technology supply chain. An overall judgement of ***Very High to Very Low***

Deliverability - a measure of the extent to which the Carbon Trust can act to facilitate delivery of an advantaged position within the intervention, as measured by such factors as:

UK competitive position	Reflects the relative size and competence of the technological resource within the UK that be brought to bear to achieve a desired result. Judged as: • Dominant - leader, setting pace and direction, high commitment, funds and creativity • Strong – high commitment and effectiveness, sets new direction, recognised as strong player in breadth or depth • Favourable - leader only in niches, has capabilities that can be exploited to improve competitive position • Tenable -in catch-up mode, not differentiated from competitors • Weak
Development Status and Technological Potential	Reflects the extent to which there is scope for further innovation and advance in the key technologies embodied within the intervention. The key technologies are *Judged as:* • Emerging - Long time to commercialisation (10+ yrs.), commercial and technical outcome uncertain, R&D costs very uncertain, high durability of competitive advantage. • Growing – Moderate time to commercialisation (5-10yrs.), commercial and technical outcomes fairly high degree of certainty, R&D costs moderately uncertain, moderate durability of competitive advantage. Radical innovations. • Mature – Near term commercialisation (1-5 yrs), commercial and technical outcomes and R&D costs highly predictable, durability of competitive advantage is limited. • Aging – very near term commercialisation, technical and commercial outcomes and R&D costs very predictable, short term competitive advantage. Incremental innovations.

Barriers to commercialisation	*<u>Barriers arising from normal operation of market forces.</u>* **Cost** of new technology can rarely meet normal commercial tests except in niche or premium markets; **Real or perceived risks** in new technologies which makes investors wary and limits markets to early adopters, included in this is uncertainty over future fuel supplies **Infrastructure investments** and costs (includes physical infrastructure, setting up training and maintenance support, spare parts supply etc.) can involve a range of players from different market sectors. **Capital stock turnover** affects the pace at which technologies can enter the market. **Environmental and socio-economic barriers** may be present (e.g. noise and visual appearance, social disruption) that render the technology unacceptable to the public even though the overall impact is beneficial. **Financial exposure**, in terms of significant R,D&D, capital and marketing costs, may deter technology uptake. **Knowledge and experience** about particular technologies and how they might be employed/deployed in a particular end-use limits analysis, understanding and confidence of potential benefits **Regulations or market access restrictions** such as additional procedures and certification. *<u>Barriers arsing from failures in market structure</u>* **Organisation of the market** may lead to inefficient or ineffective decisions - this may occur were initial design and investment decisions do not accrue to the end user as in the building sector. **Unremunerated benefits** where a technology achieves environmental benefits at a cost that the end user is not willing to pay. ***Judged as Very High to Very Low depending on the number and severity of barriers that exist***