Costs and Finance of Abating Carbon Emissions in the Energy Sector

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October 20, 2006

Scope and Purpose of Paper

This paper brings together several background notes and calculations prepared for the Stern Review. It is in three parts:

Part 1: Technologies and Costs

Part 2: Aggregate Costs and Financial Requirements of Carbon Abatement

Part 3: Policies and Finance

The comments and feedback from members of the Stern Review team were stimulating and helpful. I would especially like to thank Vicki Bakhshi, Chris Taylor, Alex Bowen, Siobhan Peters, Sophie Cruickshank and Dimitri Zenghelis for our discussions on the topics below and of course Nick Stern for inviting me to contribute to the background materials for the Review and for identifying so clearly the contribution he sought. It was a pleasure to be associated with all the Stern team.

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PART 1: TECHNOLOGIES AND COSTS

1.1 Technologies and Practices

There is no shortage of technological options and practices that would enable the world to enjoy the benefits of using energy while moving to a low carbon energy system. In fact, the world's energy needs could eventually be met several times over by non-carbon energy resources, and through improving efficiency in energy consumption and use. There are also possibilities for using fossil fuels—coal and gas for electricity generation in particular—while capturing and sequestering the carbon dioxide emissions that would otherwise be released to the atmosphere.

Surveys are provided in World Energy Assessment by the UNDP and World Energy Council (2000), the Third Assessment Report of the IPCC, a review by Gross and Anderson for the PM's Strategy Unit (2002), Watson, Zinyowera and Moss (1996) and the influential papers by Pacala and Socolow (2004 and 2006). In brief, the following are some of the key options:

1) Energy efficiency in homes, industry, transport and commerce:
    - *Vehicle fuel economy*. Pacala and Socolow draw attention to the savings that would arise if average vehicle fuel efficiency were raised from 30 to 60 mpg. The hybrid vehicle, to name just one possibility, could take us a long way down this route, as could the hydrogen fuel-cell vehicle. Congestion pricing, which is becoming increasingly practicable thanks to developments in information technologies, is another practice that would improve fuel efficiency in transport.
    - *Buildings*. Buildings account for about one-third of energy consumption. There is a large industry engaged in improving the efficiency of space heating, cooling, water heating, lighting, air conditioning and refrigeration.
    - *Industry and commerce*. There is similarly a large industry engaged in improving efficiency in the use of heat, light, motive power, air conditioning and refrigeration in industrial processes and commerce.
2) The substitution of natural gas for coal in power generation. The UK has gone a long way down this route on account of the economic and local environmental attractiveness of using natural gas.
3) The use of coal and natural gas for electricity generation, with the carbon dioxide being captured and stored in geological formations. The UK is currently exploring this option for enhanced oil recovery from depleted oil fields in the North Sea. In many regions, depending on the permeability of the coal beds, it might also be used for enhanced coal-bed methane recovery, also on a carbon neutral cycle.
4) Nuclear power for electricity generation.
5) Renewable energy. This is a diverse resource, and far more plentiful than often thought (see Annex 5):

- Onshore and offshore wind. The offshore resource is especially abundant.
- Wave and tidal energy, including tidal streams;
- Solar PVs. These are especially promising in developing regions, where the incident solar energy is 2-3 times greater than in the UK and the energy is more uniformly distributed throughout the year;
- Solar-thermal technologies, both for heating and for power generation. Again, these are most promising in developing regions;
- Biomass crops for heat, power and liquid fuels for transport. In developing regions energy from biomass can be produced in ways that would restore degraded lands, forests, watersheds and ground water resources;
- Organic biomass wastes for CHP, a practice widely used in Europe, and also for producing biofuels for transport;
- Geothermal energy, which could become a significant resource given the progress in the oil and gas industry with deep drilling technologies.

6) The production of hydrogen from gas and coal, with the carbon dioxide being sequestered. It is often argued that this would be a low cost route to opening up the 'hydrogen economy'. The hydrogen could serve major energy markets, e.g.

   - For transport fuels, either for fuel cell or internal combustion engine vehicles;
   - Heat and power in homes, industry and commerce, e.g. using micro-turbines or fuel cells for decentralized heat and power;
   - The industrial fuel market.

7) The production of hydrogen by electrolysis from renewable energy and nuclear power, again for use as a fuel for homes, commerce industry and transport.

8) The production of hydrogen from biomass, with carbon capture and storage. This roughly doubles the carbon value of this resource, first for producing a fuel with low carbon emissions, second for 'scrubbing' and sequestering CO_2 from the atmosphere.

The 'hydrogen option' is of course not a primary energy resource, but a means of storing and utilizing renewable and nuclear energy, and also energy from fossil fuels while avoiding carbon emissions to the atmosphere. For up to about one quarter or one third of electricity supplies, 'intermittent' renewables can be used with moderate amounts of backup capacity to maintain supply reliability; but for larger levels of use, in electricity and in transport, some means of storing the energy will be required, with hydrogen being the likely (but not the only) option. Nuclear power will likewise be confined to base load electricity markets, and will also be unavailable for transport, again unless some means of energy storage is developed.[1]

As the studies by Pacala and Socolow have shown, the above options are *already proven and available*; all are to be found in use in some parts of the world, and in some cases—renewable energy, nuclear power, hydrogen production for example—their use is extensive. As discussed in the Stern Review, 10 Gtons of carbon abatement, perhaps more, may be needed by 2050; Pacala and Socolow showed that each of the 15 technologically proven options they review would be capable of producing at least 1 Gigaton of carbon abatement per year (GtC/yr) by 2050; in fact several options are capable of providing two or more GtC/yr of abatement. (See also Annex 6.)

Nor can the possibilities for an economic surprise be ruled out, in the form of discoveries and innovations not currently factored into mainstream engineering analysis of energy futures. Examples might be polymer-based PVs, with prospects for 'reel-to-reel' or batch processing, on which some excellent research is afoot; the generation of hydrogen directly from the action of sunlight on water in the presence of a catalyst (photo-electrolysis); novel methods and materials for hydrogen storage; small and large-scale energy storage devices more generally, including one known as the regenerable fuel cell; nuclear fusion; and new technologies for improving energy efficiency. There is an abundance of ideas, and an excellent research base in many countries for future policies to build on. There is no evidence at all, in fact the opposite, that discovery and innovation in the energy sector has run its course; it is still capable of yielding rich and unanticipated rewards. Annex 1 provides a chart summarizing the current state of development of selected technologies.

The scenarios of greenhouse gas emissions surveyed by the IPCC, and the scenarios produced by the Panel itself, attracted much comment on the sheer spread of possibilities ahead (see Annex 2). Some scenarios point to emissions rising 5-fold or more from today's levels, others to emissions declining to one quarter or less, such that a process of *de*-cumulation might even be feasible in the long-term. There are two points to be noted about this work. *First*, most scenario exercises—and all those produced by the IPCC—assume continued economic growth, since the aim (surprisingly it was often left tacit) was to show that the low as well as the high emissions trajectories could be fully reconciled with success in economic growth and development. The latter would include an expansion of world energy supplies to perhaps two or three times their present level of 450 Exajoules (EJ) per year.[2] Such scenarios are easily replicated through simulation methods, and will be discussed further in Part 2 below.

Second, there is one common feature that distinguishes the low from the high emission scenarios, and this is technological change and the policies that bear on it. Not

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[1] For peak load electricity supplies the old options of compressed air and pumped storage are being re-examined. In countries with good hydro resources, solar and wind energy can be good complements, by reducing the drawdown of the reservoirs in the dry seasons, and by leaving the reservoirs fuller at the end of the wet seasons of dry years.

[2] 1 EJ = 10^9 Gigajoules (GJ) = 278 billion kWh ≈ 24 million tonnes of oil-equivalent energy.

surprisingly, the low emission trajectories all assume a shift toward the sorts of low-carbon options listed above.

There are often painful disagreements over *which* technologies would be the most appropriate or cost-effective—as between nuclear power and renewable energy in the UK for instance—but there is little disagreement on the basic point that deep cuts in carbon emissions are technically achievable.

1.2 Relative Costs

There are numerous estimates of the costs of the technologies, which are under continual review by governments and international agencies. No two studies agree precisely, and most admit to appreciable uncertainties. Estimates vary with:

- The world prices of oil, gas and coal;
- Assumptions as to rates of innovation;
- Location, especially for renewable energy sources such as wind, solar energy, marine resources and biomass. Costs differ within a country, and even more between countries;
- The constraints facing a country: the availability of land for biofuels for example, or for onshore wind; the opportunities for sequestering carbon; nuclear waste disposal issues and costs; local planning requirements, and so forth.
- The supply methods chosen. There are for instance a dozen or more routes for hydrogen production, transmission and distribution, which include both centralized (large-scale) and decentralized approaches (medium- and small-scale). There is a similarly large number of routes to producing biofuels.
- The weights of each technology in the supply mix—how much emphasis is given to nuclear power, wind, biomass, distributed generation, and so forth.

The cost estimates shown in Table 1 are interpretations of several recent major studies, and are put forward here with the customary health warning. They are divided into three market categories—electricity, gas and transport fuels. The costs per unit of energy are shown for each technology relative to that of the fossil fuel it would displace, the so-called ‘marker’ technology. The marker technologies are coal and gas for electricity generation, petrol and diesel for vehicle fuels, and gas for heat in homes and industry. They assume a crude oil price of approximately $50 per barrel and an industrial price of natural gas of £4/GJ (roughly £4/mBtu or 40p/therm). A drop in the world oil price to $30/barrel or of natural gas to £2/GJ (its level only three years ago) would raise the estimates of relative costs shown in the last column appreciably.

Uncertainties in the estimates are dealt with by specifying ranges for each technology. Examples are shown in Annex 3, where the ranges shown use statistical (Monte Carlo) methods to combine the variances of the prices for oil, gas and coal with the variances of the costs of each technology. The treatment of uncertainties is discussed further in Part 2.

Table 1.1: Relative Costs of Selected Low Carbon Supply Options

Low Carbon Technology	**Marker Technology**	**Cost unit**	**Cost of Marker**	**Cost of Low Carbon Technology**	**Net cost, as % Marker**
Near term estimates (about 5-10 years)					
………...………………………. **Electricity Markets** …………………………...					
Electricity from gas with CCS	NGCC or coal	p/kWh	2.6	4.8	85
Electricity from coal with CCS	NGCC or coal	p/kWh	2.6	4.3	65
Nuclear power	NGCC or coal	p/kWh	2.6	3.9	49
Electricity from energy crops	NGCC or coal	p/kWh	2.6	6.3	143
Electricity from organic wastes	NGCC or coal	p/kWh	2.6	6.9	167
Onshore wind	NGCC or coal	p/kWh	2.6	4.7	82
Offshore wind	NGCC or coal	p/kWh	2.6	6.8	164
Solar thermal (v, sunny regions)	NGCC or coal	p/kWh	2.6	11.7	353
PV for distributed generation (sunny regions)	Grid electrcty	p/kWh	7.9	18.0	127
dCHP using H from NG or coal with CCS	Grid electrcty	p/kWh	7.9	20.6	160
……………………………………. **Gas Markets** …………………………………..					
Hydrogen from NG or coal (CCS)--industry	NG	£/GJ	4.0	7.7	93
Hydrogen from NG or coal (CCS)--distributed	NG	£/GJ	6.0	15.5	158
Electrolytic hydrogen--industry	NG	£/GJ	4.0	19.7	392
Electrolytic hydrogen--distributed	NG	£/GJ	6.0	27.1	352
Biomass for heat--distributed	NG	£/GJ	6.0	9.4	57
……………………….. **Transport Markets** …………………………..					
Bioethanol	Petrol	p/ltr	29.5	28.4	-4
Biodiesel	Diesel	p/ltr	29.5	47.3	61
Hydrogen ICE vehicle--fossil H (+ CCS)	Petrol	p/lt. equv	29.5	54.2	84
Long term estimates (over 20 years):					
……...………………………. **Electricity Markets** …………………………...					
Electricity from gas with CCS	NGCC or coal	p/kWh	2.1	4.5	113
Electricity from coal with CCS	NGCC or coal	p/kWh	2.1	3.8	79
Nuclear power	NGCC or coal	p/kWh	2.1	3.5	67
Electricity from energy crops	NGCC or coal	p/kWh	2.1	4.8	129
Electricity from organic wastes	NGCC or coal	p/kWh	2.1	4.1	98
Onshore wind	NGCC or coal	p/kWh	2.1	2.8	32
Offshore wind	NGCC or coal	p/kWh	2.1	4.5	114
Solar thermal (v, sunny regions)	NGCC or coal	p/kWh	2.1	8.8	319
PV for distributed generation (sunny regions)	Grid electrcty	p/kWh	7.9	9.0	13
dCHP--H from NG or coal with CCS	Grid electrcty	p/kWh	7.9	7.6	-4
……….………………………. **Gas Markets** …………………………………..					
Hydrogen from NG or coal (CCS)--industry	NG	£/GJ	4.00	6.3	58
Hydrogen from NG or coal (CCS)--distributed	NG	£/GJ	6.00	13.1	119
Electrolytic hydrogen--industry	NG	£/GJ	4.00	14.1	253
Electrolytic hydrogen--distributed	NG	£/GJ	6.00	20.5	242
Biomass for heat--distributed	NG	£/GJ	6.00	9.4	57
……………………….. **Transport Markets** …………………………..					
Bioethanol	Petrol	p/ltr	29.5	30.8	4
Biodiesel	Diesel	p/ltr	29.5	45.1	53
FC Hydrogen vehicle--fossil H (+ CCS)	Petrol	p/lt. equv	29.5	21.6	-27
FC Hydrogen vehicle--electrolytic H	Petrol	p/lt. equv	29.5	71.7	143

(a) *Electricity Markets*:

Opportunities for substitution are most abundant in the electricity markets. They include the continued use of coal and gas with carbon capture and storage (CCS), nuclear power, the full range of renewable energy technologies, and decentralized forms of generation and combined heat and power (dCHP). For CCS, nuclear power, energy from onshore wind, and energy from organic wastes and fuel crops the near term the costs of the low carbon options are 40 to 100% above the generation costs of the marker. The costs of offshore wind, solar energy and dCHP are presently much higher.

The uncertainties are too large for the estimates to be used to identify the least cost options—and the same applies, I believe, to other studies. For example, nuclear power appears to be less costly than CCS, offshore wind or the use of organic wastes for heat and power; but a 30% escalation in its costs, which has not been unprecedented in the industry, and/or a requirement that it makes a financial provision for waste disposal and decommissioning, would make it the more expensive. A drop in the price of gas from its currently high level of £4/GJ would also reshuffle the pack. The results of optimization models, such as the MARKAL model developed by the IEA, change kaleidoscopically with small changes in relative cost assumptions.[3]

It should be emphasized that, with the exception of distributed generation, the table is comparing costs at the power station terminals. However, transmission and distribution costs account for one half to two thirds of supply costs such that when the impact of the above costs on the retail prices to industry, commerce and homes is being assessed, the percentage effects are roughly one half to one third of the figures just noted. The *expected* incremental costs of options available over the current generation of investments span a range of 20 to over 50 % of electricity supply costs today.

In the longer term (>20 years) the scope for innovation should reduce the costs of the low carbon options (see the second column). However, the costs of generation from coal or gas will not stand still, even if, as assumed in the calculations shown here, the costs of coal and gas remain at today's levels; the efficiencies of the power stations are likely to improve and their capital costs to fall.[4] The expected costs of the low carbon technologies relative to their markers are likely to decline somewhat but remain higher, with the possible and interesting exception of distributed generation. In other words, barring economic surprises or major shocks to oil and gas prices policies will need to be premised on the assumption that tax and other incentives will be required to encourage the emergence and use of low carbon options.

The most significant declines in costs are likely to be those for the three categories of technologies that are the most expensive in the near term—solar energy in sunny regions,

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[3] This is a striking feature of the 70 runs of the model undertaken for the 2003 Energy White Paper (see DTI, 2004).

[4] This happened over the period 1960-1990, and was one reason why nuclear power found it difficult to compete with coal and gas. The efficiencies of coal- and gas-fired stations rose from the low 30-percent range to 45% in the case of coal and 55% in the case of gas. The unit capital costs of the stations also fell appreciably.

offshore wind and dCHP.[5] The technologies are modular, have short lead times, and are fertile areas for innovation both in the technologies themselves and in their manufacture and installation; they are also high up on their learning curves, which tend to be steeply declining in the early phases of investment. Depending on the rates of innovation and scale economies in manufacture and installation, their costs could conceivably become *less* than those of the options that have the most promise in the near term. Indeed, solar PVs in sunny regions and dCHP (using micro-turbines or fuel cells) may reduce electricity supply costs relative to today's levels, because they also save on the costs of and losses in transmission and distribution.

Limitations to the use of the various technologies will however surface as market shares rise, pushing costs to the upper end of the ranges just noted, and possibly above. No technology is exempt. Nuclear power will face the problem of long lead times (5-7 years), planning consent and the long-standing problems of waste disposal and decommissioning problems. It will also be confined to base load operation, until there is a willingness to invest in short term storage technologies such that it can respond to daily load variations. Onshore wind will eventually be limited by sites, while both onshore and offshore wind, like nuclear power, will require some means of storage to cope with daily variations in demand and to avoid spillage of energy in high wind periods. Solar energy in sunny regions will likewise come up against the storage problem at higher levels of market penetration. Carbon capture and storage plant are capable of filling in the gap since the power plant can be scheduled to meet demand fluctuations; but concerns as to the integrity of the sites and long term leakages are likely to grow. Lastly, electricity from biomass will eventually be limited by its land requirements in the case of crops.

As such limitations begin to bite, carbon abatement will move from a relatively 'easy phase' to a far more difficult one technologically. As will be seen, this will also be true in the markets for gas and transport fuels. The common problem is energy storage. Coal, oil, gas and biofuels have the immensely valuable properties of being stores of energy in and of themselves, and of flexibility in use; this is not true of the outputs of nuclear power stations or renewable energy generators (other than those using biomass). Hydrogen as a storage medium and energy carrier seems to offer the best prospects; its costs, if produced from coal or gas with carbon capture and storage, are comparable to those of oil fuels, but are much higher if produced electrolytically (see Table 1). In addition, there are the technological challenges of storing hydrogen itself. There are other options for short-term storage such as compressed air, pumped storage, batteries, regenerable fuel cells, and thermochemical and other devices; however, options for long term storage will also be needed. There is no more important an area for R&D than energy storage—of hydrogen and electricity especially.

(b) *Gas Markets*:

The main near and long term option for reducing emissions from the combustion of natural gas would be the production of hydrogen from natural gas itself or from coal through coal gasification, with the carbon dioxide being captured and sequestered. There

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[5] The same might apply to marine renewables, an option not costed here, as they are in the RD&D phase.

are two main components to the incremental cost: first the costs of CSS, and second the costs of distributing hydrogen, which requires materials that resist hydrogen embrittlement.[6] It is possible that the costs of the infrastructure for distribution would be 30-50% higher than for natural gas. To minimise costs the best policy would be to gradually make the infrastructure compatible with hydrogen as it is being renewed; existing infrastructures are thought to be capable of accommodating a 20%-hydrogen/80%-natural gas mix, so a policy of introducing and gradually increasing the 'blend' of hydrogen in the natural gas network is thought to be feasible.

Relative to the costs of natural gas supplies today, the *medium-term* costs would probably be about 100% higher for industrial hydrogen and 150% for domestic hydrogen. In the *longer term*, costs may come down with improvements in conversion efficiency and reductions in the costs of CCS.

Electrolytic hydrogen, as the table shows, and as is well known, is considerably more expensive than hydrogen derived from gas or coal gasification with CCS. In fact it is over twice the cost. It is likely to be turned to only if or where CCS is unacceptable, e.g. on account of the likelihood of leakages from the sinks.

Looking ahead, there may be one possible exception, which is hydrogen produced by photo-electrolysis, the prospective costs of which are not estimated above. This is an important area for research.

(c) *Transport Markets*:

The most promising near-term options are bioethanol and biodiesel. The costs of bioethanol are currently comparable to those of petrol (the costs of which are about 30p/litre or £10/GJ), and of biodiesel about 45p/litre. The land requirements of biomass will clearly be an issue for very large levels of production. Pacala and Socolow estimate that 34 million barrels per day could be produced in an area equal to about 15% of the world's cropland, sufficient to account for 1 Gigatonne (one of their 'wedges') of carbon abatement. However, through a proper choice and mix of species biomass projects can be designed to have multiple benefits: to restore watersheds, reduce run-off and improve groundwater resources; to improve micro-climates (especially in arid regions), increase soil moisture content, the availability of compost and agricultural yields; and to improve biodiversity. The key will be to avoid over-specialisation in crops and to regard energy as a by-product of what should be investments serving environmental as well as economic purposes.

The Royal Society is looking at possibilities for improving yields.[7] Presently, yields are around 10 dry tonnes per hectare and 18 GJ/tonne, or perhaps 50 GJ/ha after allowing for losses in conversion to liquid fuels. In contrast, the net yield of a solar scheme in developing regions would be nearly 150 times this amount, or 7,000 GJ/ha (5,000GJ/ha if

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[6] The point is often made that town gas from coal, which constituted much of the industrial world's gas supplies until 40 or so years ago, was in fact 40% hydrogen (the rest being carbon monoxide), so we have had experience with having hydrogen in the gas system.

[7] Report to be published next year.

converted to hydrogen), and in northern climates about 3,500 GJ/ha. The main issues, if we were turn to hydrogen as a transport fuel, do not relate to yields, which are more than two orders of magnitude greater than those for crops, nor to our capacity to produce it in sufficient quantities, but, once again, to storage and cost.

The near-term cost generating and distributing hydrogen from fossil fuels (with CCS) is around £8/GJ for industrial hydrogen, and would probably be around £12/GJ for hydrogen distributed to a vehicle fuelling station. Perhaps surprisingly, these figures compare well with £10/GJ for petrol and £9/GJ for diesel fuels based on a $50 per barrel oil price. The longer term costs may be 10-20 % less than this. Even for electrolytic hydrogen, the longer term costs do not look prohibitive, about £17/GJ (equivalent to 60p/litre of petrol). In addition, if used in a fuel cell vehicle the fuel efficiencies would be approximately doubled, giving fuel-efficiency weighted price equivalent of ~ 30p/litre.[8]

Hence the *fuel costs* of motoring using hydrogen fuels could conceivably remain the same as or even fall relative to today's levels, as indicated in the penultimate column of Table 1.2 below. The main issues ahead therefore relate less to the fuel costs of motoring, and more to the costs and difficulties of storing the hydrogen, fuel cell development and the redesign and engineering of the vehicles. It is thus necessary to ask, what would the hydrogen vehicle add to the cost of motoring compared with today's levels?

A comprehensive study of costs has been undertaken by the EU (the CONCAWE Report, 2003)[9], which examined a range of vehicle concepts, including hydrogen vehicles powered by internal combustion engines and fuel cells. A report for the UK Department of Transport by IEA Technologies has extended the estimates further.[10] The estimates shown in Table 1.2 are based on an interpretation of these sources, which cover several vehicle types and the components of cost (power trains, storage tanks, fuel cells, batteries etc) in some detail. The estimates of the incremental costs of hydrogen vehicles are expressed relative to those of a petrol fuelled vehicle today costing about £12,000. The following table adds the costs supplying hydrogen, and converts the incremental costs to a cost/km after allowing for the fuel efficiency of the vehicles.

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[8] It should be added that the emergence of the full hybrid vehicle could also reduce fuel consumption of petrol and diesel vehicles by half, so the fuel cell vehicle is (like so many other technologies) competing with a moving target.

[9] This work was carried out jointly by representatives of EUCAR (the European Council for Automotive R&D), CONCAWE (the oil companies' European association for environment, health and safety in refining and distribution) and JRC/IES (the Institute for Environment and Sustainability of the EU Commission's Joint Research Centre), assisted by personnel from L-B-Systemtechnik GmbH (LBST) and the Institut Français de Pétrole (IFP). It was published in 2003, and is being updated.

[10] The report is still to be published. I am grateful to Nikolas Hill of AEATechnologies for sharing their estimates with me, which I have drawn on below.

Table 1.2: Incremental costs of hydrogen and petrol-engine vehicles compared

Vehicle Type	Year	Fuel	Increm-ental Costs of Vehicle £	Fuel Costs		Total Costs Including Incremental Vehicle Cost p/km
				£/GJ	p/km	
Petrol vehicle today: (basis for comparison)		Petrol	0	10	1.7	1.7
Hydrogen vehicles:						
ICE	c2015	NG or Coal, with CCS	3500	12	2.0	5.8
Fuel cell	c2015	NG or Coal, with CCS	8000	12	1.4	10.1
Fuel cell	c2015	Electrolysis	8000	25	2.1	10.8
ICE	2025	NG or Coal, with CCS	2000-2500	10	1.7	3.9-4.4
Fuel cell	2025	NG or Coal, with CCS	2500-3000	10	0.8	3.5-4.1
FC cell	2025	Electrolysis	2500-3000	20	1.6	4.3-4.9
ICE	2050	NG or Coal, with CCS	1500-2000	10	1.7	3.3-3.9
Fuel cell	2050	NG or Coal, with CCS	1500-2000	10	0.8	2.5-3.0
Fuel cell	2050	Electrolysis	1500-2000	15	1.2	2.8-3.4

Source: CONCAWE Report (2003), and discussions with Nik Hill of AEA Technologies. These estimates assume 170MJ/100km for petrol and ICE hydrogen vehicles, and 80 MJ/100km for the fuel cell vehicle. Note that there are likely to be hybrid concepts for all of the options shown in the table, which would further improve vehicle efficiencies; these have not been costed. Improvements in fuel efficiency with hybridization and other factors are considered in the energy demand estimates in Part 2 below. To estimate the total costs the costs of the vehicles are annualised and divided by the assumed average annual distance travelled, 15,000km/ year. A 10% discount rate and vehicle life of 10 years are assumed.

In sum, the costs of supplying energy for transport would be comparable to those of supplying energy today, and may even become lower on a pence per km basis, once the extra efficiency of fuel cell vehicles are taken into account. It is the extra costs of the vehicles, including the onboard storage of hydrogen, that pose the main technological challenge.

1.3 Conclusions

1. *Emissions abatement*: Deep cuts in carbon emissions are technically feasible over time. There will be unavoidable lags in reducing emissions, on account of the times required to ‘ramp up’ production from an initially small base; the limitations initially high costs will place on the initial scale of markets; investment lead times; the growth of world energy markets; and the longevity of existing assets. But a transition to a world energy economy

in which carbon emissions are reduced to very low levels has been shown by many studies to be technically feasible.

2. Options available or emerging: The range of technological options is wide, and they are not mutually exclusive. Most studies rightly argue for a broad portfolio of investments, in part because several technologies will run into constraints as their market shares rise—the land requirements of biofuels, issues of waste in the case of nuclear power, and the need to develop hydrogen and other storage technologies to cope with intermittency in the long term and to meet the needs of transport.

3. *Costs*: In absolute terms the effects on energy costs may be large, as summarized in table 1.1 and 1.2 above and in the figures in Annex 3. Nevertheless they are not far removed from the costs of using fossil fuels today and, as discussed in Part 2 below, turning to them on a large scale would not be disruptive to economic growth.

4. *The scope for reducing costs through discovery and innovation*: This is appreciable, both in the technologies themselves, and in their manufacture, since most are modular and are capable of benefiting from scale economies and further developments in manufacturing and installation techniques. The history of energy supply and use over the past two centuries is replete with extra-ordinary examples of successful innovations effecting every walk of life, and there is no evidence for thinking that the future will be different, quite the opposite.

PART 2: AGGREGATE COSTS AND FINANCIAL REQUIREMENTS OF CARBON ABATEMENT

2.1 Approach

The analysis first estimates the average costs per tonne of carbon abated of reducing carbon emissions from fossil fuels at various points in time. It then multiplies the estimates to calculate the total costs of reducing carbon emissions by amounts the Stern Review estimated would be needed to stabilise carbon accumulations in the atmosphere at 550 ppm. It is concerned with CO2 emissions from energy production and use only, as other parts of the Review dealt with emissions from other sectors and other greenhouse gases. The total costs are expressed in absolute terms; then as a percentage of energy supply costs; and finally as a percentage of World Product.

The approach just one of several ways of estimating the costs of mitigating climate change, which are reviewed in the Stern Report. Economists have generally preferred to use macro-economic growth models with varying degrees of sector disaggregation. Such models have many merits (noted later), but one demerit is that the basis for their results is often implicit in the model structures and assumptions, for example in how the substitution between carbon and low carbon technologies is modelled, in the elasticity of substitution, and in the modelling of technological change, which may be treated exogenously or endogenously. Results differ appreciably between models and, given the complexity of the models, it takes an heroic effort, such as that of the review of Barker, Koehler and Villena (2002), to identify why particular results have been arrived at and why they differ—how sensitive the results are to the modellers' assumptions about oil and gas prices, for example, to the rates of innovation, and to the underlying parameters.

Quite a different approach to estimating costs is to ask the questions, what kinds of technologies and practices are likely to be needed to achieve a low carbon economy? What is their availability? What constraints or other factors may limit their use? What are their current and prospective costs? How do the costs 'add up' after allowing for various systems and infrastructure requirements relating to their use? How do the estimates differ with price and cost assumptions, and with assumptions as to the portfolios of technologies that might emerge? And so on. Engineering-economic calculations can be undertaken to answer such questions[11], and serve to provide a simple and transparent check on the results of the economic models (and, as shown in the Review, the results for the most part are not far apart). This is the approach followed below:

- For each of the three main energy markets—electricity, gas and transport—a list is compiled of the fossil fuel technologies in use and their low carbon alternatives. This was done in Part 1 above. The list includes a range of renewable energy technologies, such as solar energy, wind, biofuels and hydro; nuclear power; the use

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[11] The IEA's MARKAL model takes this approach; it includes an optimization (LP) routine to choose the least cost options under particular sets of assumptions and constraints. The calculations below do not seek to find an optimum, but explore the aggregate costs of a large number of possibilities using Monte Carlo analysis, as discussed below.

of fossil fuels with carbon capture and storage; the of use any or all of the foregoing for hydrogen production; decentralised generation and CHP based on low carbon fuels; and fuel cell vehicles using hydrogen for transport. This list is far from exhaustive; geothermal and tidal and wave energy deserved more treatment for example, as did storage technologies other than those related to hydrogen production and use. If anything however this amounts to an understatement of the possibilities ahead for mitigating climate change and for reducing costs.

- Second, the capital, operation, maintenance and fuel costs are estimated for each technology. There is a growing bank of information and project experience to draw on for such estimates, and also for estimates of the error margins, which are often appreciable. Allowances are made for the effects of innovation, learning-by-doing and scale economies in manufacture and use on the future costs of both fossil fuels and their low carbon alternatives.

- Third, alternative portfolios of low carbon options are considered and used as a basis for estimating the average incremental costs of carbon abatement. The portfolios take into account the constraints on the various technologies—the land constraint on biofuels for instance, the need for storage such as hydrogen production if nuclear power or 'intermittent' renewable energy generation are to enter the transport markets, and so forth—and the lead times involved in investment and raising the level of output. As the composition of the technology portfolios is also uncertain a distribution of possibilities is considered.

Uncertainties are treated in two ways. The *first* is through 'plugging in' the error margins in the unit costs of the various technologies, and also those as to the future portfolios of technologies, to estimate the frequency distributions of outcomes using Monte Carlo methods. The *second* is through the familiar method of 'what if' calculations, such as what if oil prices were $30 or $80/barrel? or what if the rate of innovation were higher or lower than expected? and so forth. Both sets of results are presented.

All available studies agree as to the importance of energy efficiency in climate change mitigation. Over the past century alone energy efficiency—as engineers define it, as being the amount of useful heat, light or power delivered per unit of primary energy consumed—increased by an order of magnitude, in some cases by several orders; the scope for further efficiency improvements is appreciable. Below, the possibilities for efficiency improvements are reflected in an assumption of a continued decline in the income elasticity of demand over time; the effects of uncertainties in the elasticity assumptions are also analysed using Monte Carlo methods.

2.2 Unit Costs of Carbon Abatement

The costs of mitigating climate change can be estimated by comparing the average costs of low carbon technologies with those of fossil fuels, and then by multiplying the difference by the amount of energy they need to deliver to the consumer to achieve a given reduction of carbon emissions. Equivalently, the average costs per ton of carbon abated by the technologies can be calculated and multiplied by the amount of abatement required.

Estimates suitable for use in either of these approaches are summarised in Table 2.1. It lists the projected average costs of supply from fossil fuels and their low carbon alternatives; the weighted average of the difference in costs per unit of energy, taking a portfolio of options; and the weighted average incremental cost of carbon abatement.

Table 2.1: Costs per Unit of Energy and Per Ton of Carbon Abated of Energy from Fossil Fuel Technologies and Their Low-Carbon Alternatives

Market and Low-Carbon Technology	Period	(1): Cost of Supply from fossil fuels	(2): Cost of Supply from Low-Carbon Technologies	Weighted Average of Excess of (2) over (1) [b]	Weighted Average Incremental Cost of Carbon Abatement £/ton C [f]
Electricity: central electricity from coal or gas with CCS, nuclear power and renewable energy; decentralised generation from solar and small CHP generators	2005-15	6.0 p/kWh [a]	7.5-10.5 p/kWh	2.0 p/kWh	105
	2015-25	6.0 p/kWh [a]	6.0-9.0 p/kWh	1.5 p/kWh	75
	2025-50	5.5 p/kWh [a]	4.0-9.0 p/kWh	1.0 p/kWh	25
Gas (heat for homes, industry and commerce): Biomass including wastes for CHP (large and small scale); hydrogen (longer term)	2005-15	£5/GJ [a]	£9 to >£15/GJ	£4-10/GJ	330
	2015-25	£5/GJ [a]	£7 to £14/GJ	$2-9/GJ	300
	2025-50	£5/GJ [a]	£6.0 to £10/GJ	£1-5/GJ	130
Transport: Biofuels; Hydrogen (at fuel station)	2005-15	30p/litre [c]	30-55p/litre equiv [e]	15 p/litre	375
	2015-25	30p/litre [c]	30-50 p/litre equiv [e]	15 p/litre	110
	2025-50	30p/litre [c]	22-50 p/litre equiv [e]	30 p/litre	230
Weighted average incremental cost of carbon abatement: overall energy supply, £/tonC				2015	**145 ± 45**
				2025	**85 ± 40**
				2050	**60 ± 150** [g]

See Table 1.1 in Part 1 and supporting spreadsheets for details of selected technologies and of portfolios assumed. The estimates in the spreadsheets are based on interpretations from a large number of studies in the UK and abroad, and are reasonably consistent with those of international studies such as the recent review of the IEA (2006) and the framework document of the World Bank (2006). When comparing estimates across studies a PPP exchange rate of $1.6/£ has been used.

a/ An average of cost to industrial, commercial and domestic consumers

b/ For a portfolio of technologies introduced in the period (see pie charts in Figure 2.1)

c/ At $50/barrel plus refining and marketing margin of ~ 50%. The effects of oil price uncertainties are discussed below.

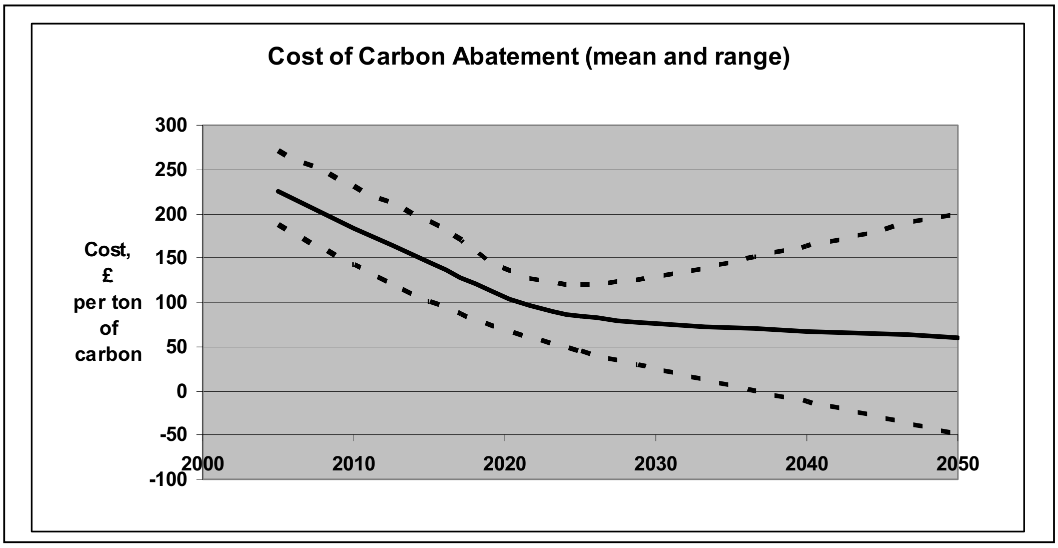
d/ A strong emphasis on heat from biofuels initially (e.g. large and small scale CHP), plus development and demonstration on centralised and decentralised hydrogen production, the latter growing over time.

e/ A strong emphasis on biofuels initially plus development and demonstration projects with hydrogen, followed by a growth of the hydrogen market, initially from CCS later from renewable or nuclear energy after 2025. In the case of hydrogen, an adjustment is made for the fuel efficiency of hydrogen vehicles. The

effects of fuel efficiency in the ICE-hybrid vehicles are implicitly included in the demand assumptions. For the b.a.u. scenario the marker technologies continue to be the petrol or diesel vehicle
f/ Calculated using the incremental costs for the portfolios shown in the pie charts in Figures 2.2a,b.c below, divided by the carbon savings. The latter equal the emissions assuming the energy supply mix remains as in 2005, minus the supply mix associated with the portfolios. Estimates rounded.
g/ The distribution is asymmetric. The actual range is from -50 to +200

Unsurprisingly, the uncertainties become larger in both relative and absolute terms the further ahead we look. In the near term, both the unit costs and the possible portfolios of the technologies can be defined within a narrower range. In the longer term the points at which physical, technological and environmental constraints begin to become important and add further layers of uncertainty—e.g. with respect to nuclear waste disposal, the availability of land for bio-energy crops, and the availability of sites for onshore wind. The effect of innovation on costs also become less clear, and the prices of the marker fuels—oil, gas and to a lesser extent coal—yet more uncertain. The estimates fan out over time, as indicated in Figure 2.1:

Figure 2.1: The Estimated Decline and the Increasing Variance of the Costs of Carbon Abatement over Time.



The importance of innovation is apparent from the estimated decline in the costs. The costs of energy production and use from all technologies have fallen systematically with innovation and scale economies in manufacture and use, apart from nuclear power since the 1970s. Several of the more modular technologies such as solar energy, fuel cells, micro-CHP and offshore wind and marine energy resources show much scope for further innovation and cost-reduction; all are fertile areas for R&D and further development. The same can be said of energy efficiency.

The assumed rates of innovation behind such calculations are not extra-ordinary. For estimating the average costs of carbon abatement in electricity generation from nuclear power or from coal with carbon capture and storage for example, costs are assumed to decline by about 15% over a 20-year period and 20% over a 50-year period. For the emerging small scale and modular technologies the learning rates assumed vary with technology, but amount to a 12 % reduction for each doubling of cumulative investment on average, which is at the lower end of the range of the estimates found in many studies.[12]

2.3 Treatment of Uncertainties

The estimated costs of nuclear power, carbon capture and storage and offshore wind span a range of ± 30%, possibly more; of the future costs of oil range from \$20 to \$80 per barrel, possibly more; and of natural gas for power generation and industry from £2 to £6/GJ (roughly 20 to 60 p/therm). The effects of learning, innovation and scale economies on future costs can likewise be estimated only within very broad limits; the future costs of modular technologies such as solar photovoltaics and micro-CHP are projected to be one third or less of those obtaining today, but also span a range of ± 30% or more. The costs of hydrogen production for industry and transport and of biofuels for heat, power and transport span a similar range.

Estimates of the portfolio of technologies that are likely to emerge are equally uncertain, as can be inferred from the large array of options that governments need to examine when assessing policies. The studies for the 2003 UK Energy White Paper explored over 60 scenarios of alternative technology mixes, including options for energy efficiency improvement; this is not untypical of a very large number of studies in other countries and at the international level. Figures 2.2a, b and c show typical portfolios for the cases of electricity supply, vehicle fuels and overall primary energy supplies respectively. The estimates for 2025 and 2050 are the means of a wide range of over 20,000 possibilities analysed in the simulations:

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[12] See McDonald, A. and Schrattenholzer,L. (2001), and IEA (2000). Learning rates are the percentage reductions in costs for each doubling of cumulative investment. Learning rages of 20% are not untypical for modular technologies.

Figure 2.2a: Shares of technologies in electricity supplies: current and long-term

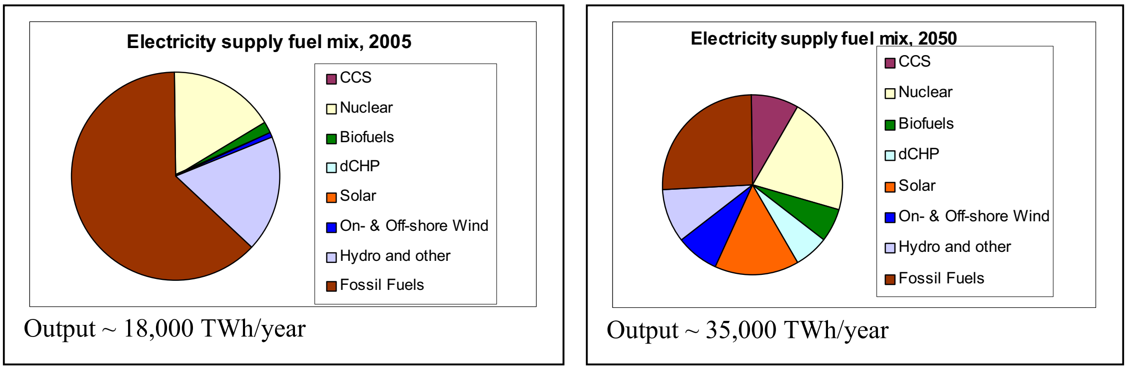


Figure 2.2b: Shares of technologies in vehicle fuel supplies: current and long-term

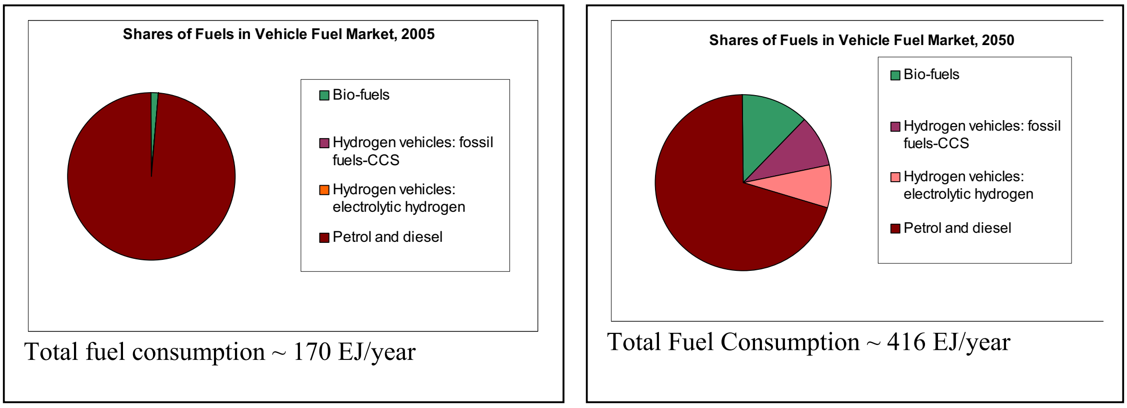
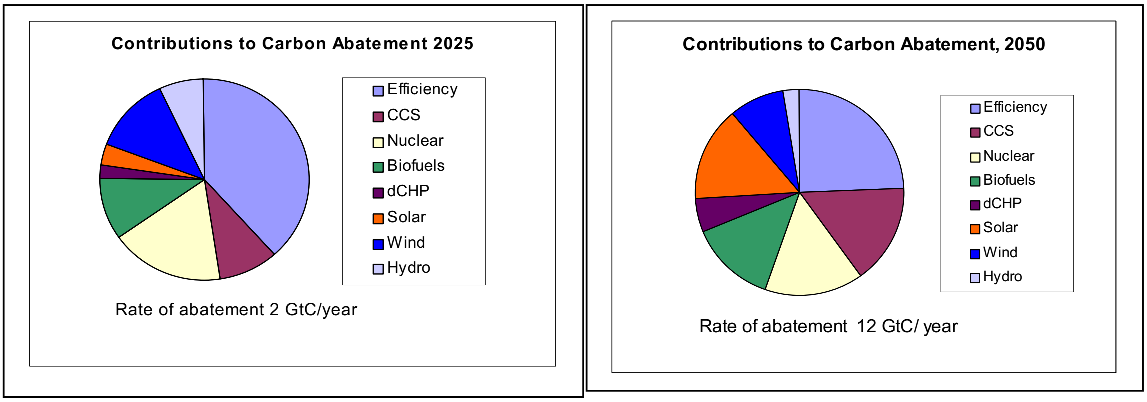


Figure 2.2c: Shares of technologies in overall primary energy supplies (including contributions to hydrogen production): 2025 and 2050.



In Figure 2.2c there is a higher relative contribution from energy efficiency in the portfolio. With the exceptions of biofuels, hydro and nuclear power—all of which face long investment lead-times—the markets for low carbon technologies are inevitably small given the small base from which they are emerging, while that for energy efficiency spans the whole of the market for energy production and consumption. Hence a higher relative contribution from energy efficiency can be expected in the medium term; as the markets for the low carbon supply technologies take root, however, there is a larger base to build on, and their relative contributions in the longer term is greater.

The simulations assume hydrogen will be used in the vehicle fuel markets by 2050. If there is to be a high level of carbon abatement, of the order of 10-12 GtC/year by then, there seems no option other than to introduce low carbon energy forms into this market. To begin, even 80-100% abatement in the electricity sector would only account for around 6 GtC/year; and bio-wastes, CHP, hydrogen in the markets for domestic and industrial gas could account for perhaps another 1-2 GtC/year. Hence without low carbon fuels for vehicles, climate change mitigation policies are likely to fall short of what is required. There are options: improvements in vehicle fuel efficiency; the development of electric vehicles; biofuels; the development of hydrogen vehicles; and combinations of the foregoing. To provide a basis for estimating costs, this study has considered a mix of fuel efficiency improvements, an expansion biofuels, and the development of hydrogen vehicles using internal combustion engines and/or fuel cells.

Although it is possible that some technologies will eventually ‘break from the pack’ and become dominant at some stage, it is too soon to identify which these will be. Over the next 25 years or so, the energy supply mix will need to become more diversified if it is to shift to a low carbon path. This is one way of reducing the risks of technology development and increasing the likelihood of success in climate change policies.

Furthemore, as discussed in Part 1, all the main options have limitations and cannot currently shoulder the task of climate change mitigation by themselves. Some technologies currently available for large-scale deployment have lower costs than others: onshore wind, biofuels for heat and transport, electricity generation from fossil fuels with carbon capture and storage (CCS), and, perhaps, nuclear power. However, even ambitious programmes for each of these technologies would fall short of what is required to stabilise carbon emissions in the long-term. Some familiar limitations are:

- The land constraints for onshore wind and biofuels;
- The availability and long-term integrity of sites for CCS;
- The long-standing issues of long lead times, waste disposal, decommissioning and proliferation for nuclear power. In addition:
- All but biofuels are confined to electricity production, such that if emission abatement levels have to reach 60% or more relative to today’s levels it will be necessary to develop low carbon supplies for the transport and heating markets.

For the last reason the portfolios considered in the present analysis include provisions for the development of the hydrogen-economy, which is capable of meeting the needs of the transport and heating markets in a carbon-neutral way using any primary energy resource.

To examine the effects of uncertainties in the portfolio, the rates of investment in each technology were defined by rectangular distributions, with the following ranges about the mean estimates up to 2025: CCS ± 30%; nuclear ± 50%; biofuels for electricity ± 50%;

solar energy ± 50%; wind ± 25%; decentralised CHP ± 50%; biofuels and hydrogen for heat and transport ± 50%; the growth rates of all technologies in the longer term ± 50%. Uncertainties as to the portfolio in the long run may be even larger, but even these ranges point to a considerable spread in possible costs, as can be anticipated from the estimates provided in the bottom three rows of table 2.1.

Lastly, the rates of investment considered were made as consistent as possible with the scenarios of emission abatement considered below in Section 2.5. Higher rates of energy growth for example, and higher levels of carbon abatement, raise the average costs of abatement, so the analysis requires a degree of consistency between the estimates of average costs per ton of carbon abated and the total abatement sought.

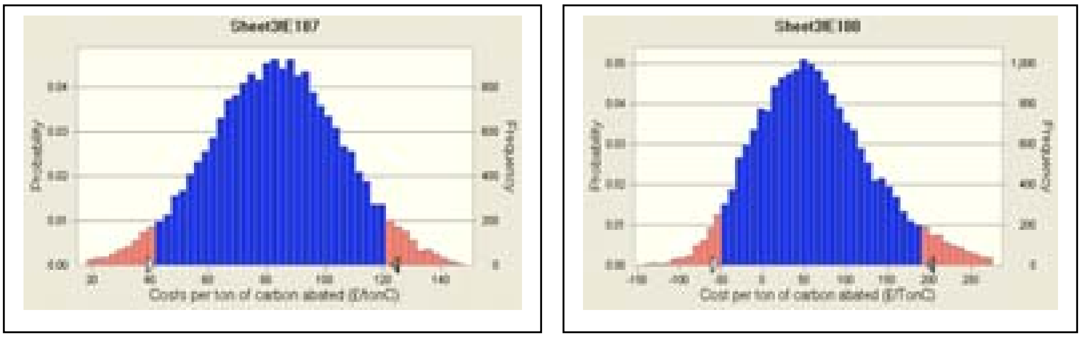
2.4 Average Costs of Carbon Abatement (£/tonC): Monte Carlo Results.

Monte Carlo methods provide a numerical means for combining the probability distributions of multiple inputs to find the probability distributions of the outputs.[13] The three distributions shown in Figure 2.3 below illustrate the results. They show the estimated probability distributions of the average costs of carbon abatement for 2025 and 2050. They consider uncertainties with respect to:

- The capital costs of each technology over time;
- Oil, gas and coal prices;
- The portfolio of technologies; as with costs this is varied over a range of possibilities.

The estimates shown in the figure correspond to those highlighted at the foot of table 2.1:

Figure 2.3: Distributions for the Average Costs of Carbon Abatement £/tonC:



2025

2050

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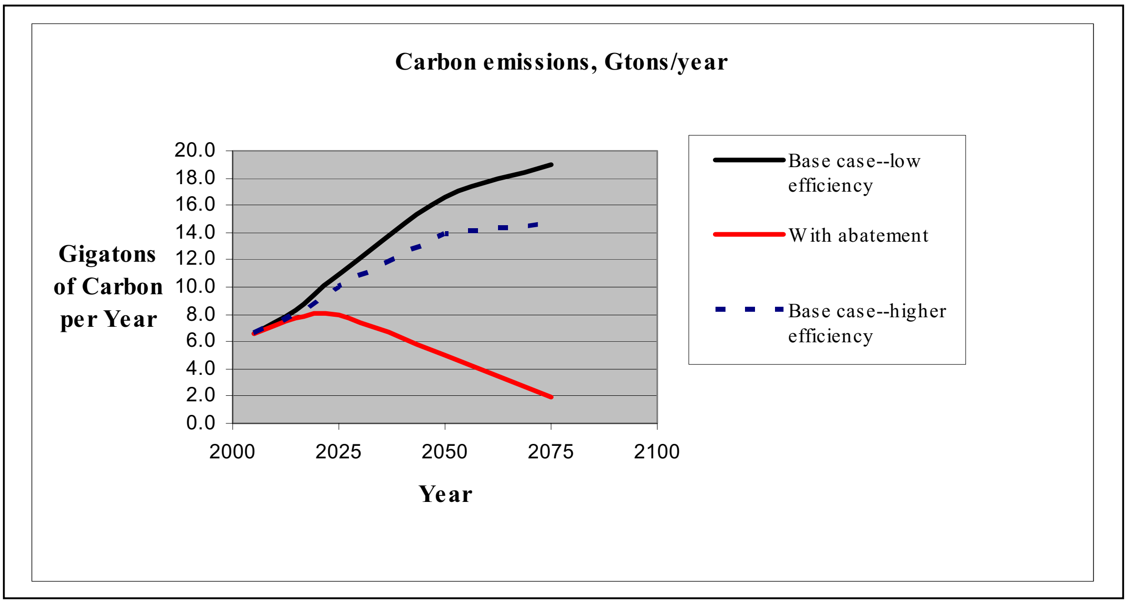
[13] The probability distributions of the costs of the various technologies and fuels are specified in the data inputs to the spreadsheets; the probability distributions of the total costs are then estimated through repeated runs or 'trials' to build up a probability distribution of possibilities. The charts in Figure 2.3 are based on 20,000 trials using Crystal Ball software.

2.5 Total Costs of Mitigation In Relation to World Product

(a) Scenarios Considered

The direct costs of mitigating climate change can be estimated by taking the difference in carbon emissions between scenarios with and without mitigation and multiplying by the costs per ton of carbon emissions avoided. For this, scenarios of emissions with and without abatement are required. The scenarios used for the present exercise are summarised in Figure 2.4; the low carbon trajectory shown corresponds to the goal of curtailing carbon accumulations to 550ppm, discussed in the Stern Review. The low emission trajectory shown is at the low end of the range of possibilities reviewed by the SRES report (2000), the IPCC Third Assessment Report, and the IEA (2006). It is a demanding scenario, requiring nearly 12 GtC of abatement by 2050 relative to the base case, or 8-9GtC of abatement assuming higher energy efficiency.

Figure 2.4: Two Scenarios of Global Carbon Emissions (from Energy Production and Use Only [a/])



a/ The Stern Review analyses non-CO2 emisions and emissions from land use and forests separately.

(b Energy Efficiency

The estimates in Figure 2.4 allow for improvements in energy efficiency. Per capita income elasticities of demand are lower (under 0.3) in the OECD than in developing country markets (where they are closer to 1.0; see Table 2.2 below).[14] The lower elasticities in the OECD are due partly to market saturation effects and partly to the steady rise in energy efficiency arising from improvements in the efficiency of lighting, heating, cooling and motive power. There are reasons and evidence for expecting

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[14] See Judson, R.A. R.Schmalensee and T.M.Stoker (1999); Joyce Dargay and Dermont Gately (1995

efficiency improvements to continue to exert a downward influence on the elasticity of demand. Hybrid vehicles for example could lead to appreciable reductions in the demands transport fuels, and heat pumps and decentralised forms of heat and power in the demands for energy in homes and commerce; but there are numerous other examples.

Table 2.2: Variation in the Per Capita Income Elasticity of Energy Demand with Per Capita Income

Per Capita Income (1985 US$ (ppp values)	Per Capita Income Elasticity
< 823	0.219
823-1430	1.098
1430-2545	1.400
2545-4249	0.784
4249-8759	0.394
>8759	- 0.312

Source: Judson, Schmalensee and Stoker (1999).

The possibility that the per capita income elasticity might become negative in OECD countries is not implausible, though Judson et al are doubtful about the estimate shown in the last row. The possibility is, however, factored into the present analysis, and is also implicit in the analysis of other studies (such as the IEA 2006, and that of the Royal Commission on Environmental Pollution for the UK in 2000), which assume larger carbon savings through efficiency than estimated here.[15]

Large gains in energy efficiency are thus thought to be possible. But there is a danger that more buoyant assumptions about efficiency will lead to an under-estimate of the costs of mitigation because they reduce the effort required on the supply side. Thus both the Royal Commission and the IEA report ignore hydrogen on the grounds that existing technologies could meet the greatly reduced energy demands without hydrogen production for purposes other than for electricity production. However, this is to encompass only a particular set of possibilities; other studies (this included) consider that the costs of developing a ‘hydrogen economy’ also need to be considered.

The differences in assumptions as to the contribution of energy efficiency bring out an issue for economic research. When analyzing growth of demand for energy there are two effects to be identified for any given set of assumptions as to prices and populations:

(i) the growth of per capita incomes times the per capita income elasticity;

(ii) the rate of improvement in energy efficiency.

Few studies have separated out these two effects empirically; available estimates of income elasticities confound the two.

(c) Effects on World Product: Monte Carlo Results

The estimates corresponding to the above scenarios, and to the costs per unit abatement discussed in the Section 2.4 are summarised in Table 2.3 below. At the global level, the

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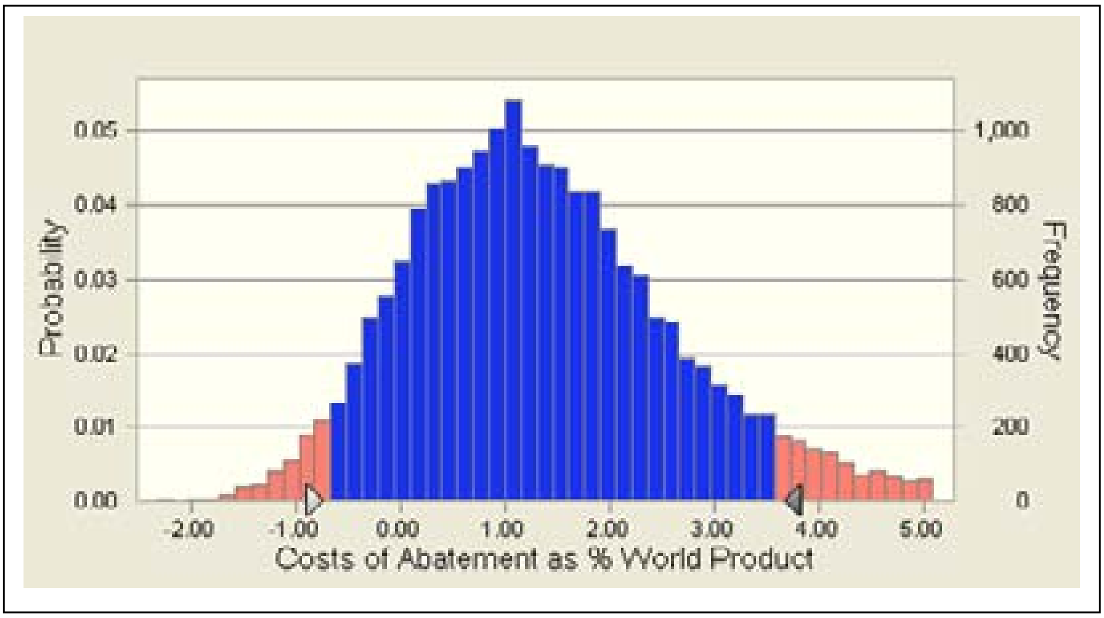
[15] Using their estimates would lead to a lower cost of carbon abatement than presented above.

estimated costs rise from around 0.3 ± 0.1 % of world product in the period up to 2020, to 0.6 ± 0.4 % in the 1920s rising to 1% by 2050, but span a very wide range by then, from under -1.0 % (a positive contribution to growth) to over +3.5%. Figure 2.5 shows the Monte Carlo results for 2050. As with all such estimates even the range (the confidence interval) is approximate; the distributions have long tails, and are often asymmetric:

Figure 2.5: Distribution of Costs of Abatement as % of World Product



The range shown is within that spanned by many other studies. The long-term estimates in most studies are in the range -0.5% to 2.5% of Gross World Product (review of Leach and Anderson, 2005), though the meta analysis by Barker et al points to a yet wider range, of perhaps -2.0 to over 4%. In the initial periods the costs per ton of carbon abated are likely to be high (Figure 2.1); but as the shares of new investments in low carbon technologies are small (around 25% by 2025) the overall effects on costs are not large, ranging from 0.3 to 0.7% of GWP.

(d) Sensitivity Studies

The possibility of the net costs eventually being negative such that GWP would be higher than would be the case without abatement has been anticipated by many studies. It rests on a more buoyant—but not over-optimistic—view of innovation, and an assumption of high oil and gas prices. Equally, technological pessimism combined with assumptions of low oil and gas prices point to the costs being as high as 3% or more of world product.

It is worth looking in more detail at the effects of particular assumptions on the estimates of costs. This is done in Table 2.3 for the following cases:[16]

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[16] Other variables, for example the demand estimates for cases (iv) to (ix) are set a their mean values

(i) A central case, corresponding to the average expected costs shown in Figure 2.1 and Table 2.1 above.

(ii) A higher cost case, corresponding to the upper ends of the estimates shown in the figure and table, which are broadly situations of low rates of innovation and low oil and gas prices;

(iii) A lower cost case, corresponding to the lower ends of estimates shown in the table, which are broadly situations of higher rates of innovation and low oil and gas prices;

(iv) A low fossil fuel price case: oil and gas prices revert to levels experienced in the 1990s: $25/barrel for oil, and £2/GJ for gas.

(v) A high fossil fuel price case: oil and gas prices persist at levels of $80/barrel and £4/GJ. A pessimistic CCS case: a persistently high cost of carbon capture and storage from fossil fuels.

(vi) A pessimistic CCS case: a persistently high cost of carbon capture and storage from fossil fuels;

(vii) Scenarios of higher and,

(viii) lower energy demand, to illustrate the effects of energy efficiency on costs, corresponding to a 25 per cent (or ±12.5 per cent) variation in the demand estimate;

(ix) A case where the incremental costs of hydrogen-fuelled vehicles is included.[17] These are incremental costs of on-board storage of hydrogen and, where a fuel cell is used, of the fuel cell. (The estimated costs of supplying hydrogen to vehicles are included in all of the above.)

Table 2.3 Global costs (sensitivity analysis of assumptions) % world product [a/]

Case	2015	2025	2050
(i) Central case	0.3	0.7	1.0
(ii) High costs of abatement (low rate of innovation and low future oil and gas prices)	0.4	0.9	3.3
(iii) Low costs of abatement (high rate of innovation and high future oil and gas prices)	0.2	0.2	-1.0
(iv) Low future oil and gas prices	0.4	1.1	2.4
(v) High future oil and gas prices	0.2	0.5	0.2
(vi) High costs of carbon capture and storage	0.3	0.8	1.9
(vii) A lower rate of growth of energy demand [b/]	0.3	0.5	0.7

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[17] See the Report for the EU Commission by the Joint Research Centre of the Commission, EUCAR (the European Council for Automotive R&D), and COCAWE (the oil companies' European Association for Environment, Health and Safety in Refining and Distribution), December 2005: Well-to Wheels Analysis of Future Automotive Fuels and Power Trains in the European Context. http://ies.irc.eu.int/WTW. The economics favour compressed hydrogen fuelling an internal combustion engine in the medium term; the fuel-cell hybrid is the favoured option for the long-term, the cost estimates of which were not available

(viii) A higher rate of growth of energy demand [b/]	0.3	0.6	1.0
(ix) Including incremental vehicle costs [c/]			
• Means	0.4	0.8	1.4
• Ranges	0.3 to 0.5	0.5-1.1	-0.6 to 3.5

a/ The world product in 2005 was approximately $35 trillion (£22 trillion at the ppp rate of $1.6/£). It is assumed to rise to $110 trillion (£70 trillion) by 2050, a growth rate of 2.5% per year, or 1 ½ -2% in the OECD countries and 4-4 ½% in the developing countries.

b/ Assuming central values of all other costs

c/ Assuming the incremental costs of a hydrogen fuelled vehicle using an internal combustion engine are £2,300 in 2025 and $1400 in 2050, and for a hydrogen fuelled fuel cell vehicle £5000 in 2025 declining to £1700 by 2050. (Ranges of ~ ± 30% are taken about these averages for the fuel cell vehicle.)

(e) Hydrogen and Transport

The effects of including the vehicle costs (in addition to fuel costs) in the estimates are shown in case (ix). This shifts the distributions of the estimates to the right by more than half a percentage point, and possibly by more on more pessimistic assumptions about vehicle development. Annex 6 also presents the Monte Carlo results when the incremental vehicle costs are included. The high end of the range shown again corresponds to low oil and gas prices and low rates of innovation, and the low end to the high oil and gas prices and higher rates of innovation.

Although there is now experience with demonstrator vehicles (of buses and cars), the longer term cost estimates are highly uncertain. For the medium term (up to 2025), estimates vary between roughly £2500 per 'standard' car for a hydrogen vehicle with an internal combustion engine to three or more times this amount for the fuel cell vehicle.[18] For the longer term, the IEA (2006, p323) comments that, depending on the pace of technology development (and also the scale of production) "the cost of a fuel cell vehicle would (likely) exceed that of a conventional ICE vehicle by USD 2,200 to 7,600 (£1500-5000/vehicle in ppp units)". Other studies for the UK government on which the above are based have pointed to the possibility of lower costs.[19]

(f) Comments on the Wider Economic Impact

The above analysis considers only the incremental costs that would be incurred directly as a result of investment in low carbon technologies. There are also indirect effects to take into account, some acting to increase and others to decrease the overall costs to an economy; these were ignored above:

- An increase in investment requirements in the energy sector will mean fewer resources going into growth and development elsewhere. Against this:
- The extra investment would be in areas that are fertile grounds for innovation, for example in the materials sciences (fuel cells, photo-conversion technologies); they

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[18] The EU Commission report by the Joint Research Centre of the Commission, EUCAR and COCAWE (December 2005), cited above, and the estimates kindly provide by Nik Hill of AEATechnologies.

[19] "UK Carbon Reduction Potential from Technologies in the Transport Sector." E4Tech Draft Final Report 24th April 2006, for the UK Department of Transport and the Energy Review Team, and a report for the Department of Transport by AEA Technologies (forthcoming).

could become sources of economic growth, independently of their contributions to climate change mitigation.

- More general effects on prices and substitution in the economy;
- Low carbon technologies would also reduce local air pollution.

Large-scale economic models are important for addressing such topics. A chapter of the Stern Report reviews the results, drawing on the meta analysis by Barker and Koehler. As noted above, their estimates span a similar if slightly wider range to the one estimated in the present paper, from roughly -2 to +4 % of GDP.

2.6 Average Total Costs and Financial Requirements of Carbon Abatement

These vary by region. For the Stern Review, there were two quantities of special interest, namely the finance required by the OECD and developing countries. The estimates are shown in Table 2.4. The cost burden would initially be higher in the OECD countries, but would grow more rapidly and eventually become much higher in developing regions with the growth of their economies and energy markets.

Table 2.4: Estimated Total Costs of Carbon Abatement by Region

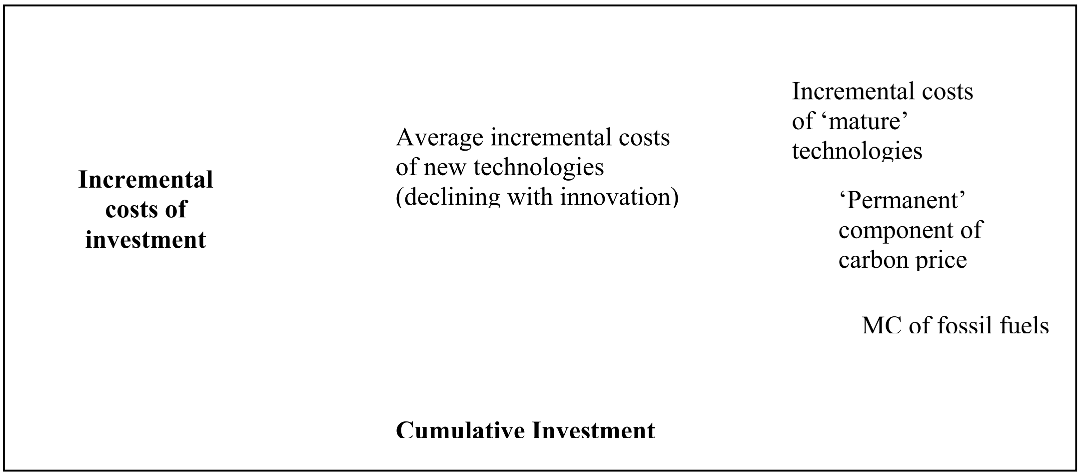
	2005	**2015**	**2025**	**2050**
Average Cost of Abatement, £/TonC	225	145	85	60
Emissions Abated Gigaton TonC (relative to emissions in year on current trends)				
OECD		0.4	1.1	2.8
East and South Asia, Latin America and Africa		0.2	1.5	7.8
FSU + Middle East Oil Exporters		0.0	0.2	1.0
Total		0.6	2.8	11.6
Total Cost of Abatement, £ billion per year:				
OECD countries		53	97	166
East and South Asia, Latin America and Africa		28	131	471
Total		81	228	636
Total, including Middle East and Former Soviet Union		87	247	698

In absolute terms the incremental financial requirements are large, but well within the scope of energy and environmental policies to raise the resources, as discussed further in Part 3. Expenditures on energy supply costs today are nearly £3 trillion per year (£1.7 trillion in the OECD and £1.2 trillion in the developing countries), or 20 or more times the incremental financial requirements of carbon abatement shown in the table for 2025.

2.7 Investment in Innovation

For several decades it will be necessary to provide incentives for the development of new and emerging technologies. Chris Taylor’s work for Chapter 16 of the Stern Review depicts the issue in a diagram of the form shown in Figure 2.6 the difference between the average incremental costs of investment in new technologies and that of mature technologies can be thought of as the cost of investment in innovation:

Figure 2.6: Components of Incremental Cost



The extra costs of investment in innovation (the area between the cost curve and the dotted line) can be estimated directly from the preceding results. Taking £50/tonC (the estimated costs post 2050) the long-term cost as a basis for the 'permanent' component, the overall cost breakdown is as shown in Table 2.5:

Table 2.5: The 'Permanent' and 'Innovation incentives' components of finance:

	2015	**2025**	**2050**
Total financial requirements, £ billions per year			
OECD	53	97	166
East and South Asia, Latin America and Africa	28	131	471
Total	81	228	636
Total, including Middle East and Former Soviet Union	87	247	698
Components: £billion/year			
The 'permanent' carbon pricing component:			
OECD	18	57	138
East and South Asia, Latin America and Africa	10	77	392
Subtotal	28	134	530
The 'innovation incentives' component:			
OECD	35	40	28
East and South Asia, Latin America and Africa	19	54	78
Subtotal	53	94	106
Innovation component as % total			
OECD	66	41	17
East and South Asia, Latin America and Africa	66	41	17

The overall requirements for investment in innovation of approximately £50 billion per year by 2015 and £70 billion per year by 2025 would be 2.5 and 3.5 times today's level, which Chris Taylor estimated is around £20 billion per year. The latter is generated by R&D programmes and incentives provided by policies such as the UK Renewables Obligation, the feed-in tariffs found in many EU countries, the portfolio standards in the US, and various grant and tax credit policies.

If indeed innovation were to reduce the average costs of abatement from around £150/tonC for the current generation of investments to one third of this level, the benefits would be immense[20], amounting to £100/tonC, such that for 10GtC of abatement by 2050 the cost savings would be £1 trillion per year.

2.8 Conclusions

Estimated average costs per ton of carbon abated: £145 ± 45/tonC in the near term, £85 ± 40/tonC in the medium term (c 2025), and £60 ± 150/tonC in the long term. A broad range is inevitable given the uncertainties about future oil and gas prices, the rates of innovation and the composition or 'mix' of technologies and practices that will be deployed in future. The higher end of the cost estimates is associated with low rates of innovation and low future oil and gas prices, the lower end with higher rates of innovation and higher oil and gas prices.

The contribution of innovation: This accounts for most if not all of the expected declines in the average costs of abatement. The positive externalities of innovations in low carbon technologies look to be very large in relation to the expenditures on innovation, even ignoring the environmental benefits of innovation. Without innovation the long-term costs would likely be around £250/tonC; with innovation, they are about one quarter of this level, a saving of nearly £200/tonC. Multiplying this by the abatement likely to be needed by 2050, which is about 10 GtC per year, points to cost-savings benefits an order of magnitude greater the expenditures on innovation required to develop the technologies. The incremental costs of investment in innovation in low carbon technologies today are about £20billion per year worldwide; they would need to rise to around £50billion per year in ten years' time and £70 billion per year in 20 years' time.

Costs as a percentage of World Product: Consistent with the findings of other studies, there the above calculations suggest that a transition to low carbon economies worldwide would not disrupt economic growth and development. The estimates are that the costs would range from around 0.2 to 0.4% of World Product in 2015, to 0.6-0.9% in 2025, and – 1.0 to + 3.5%, averaging about 1% in 2050, in a situation where the World Product is likely to rise by 300% or more over the next 50 years.

Financial Requirements: The incremental financial requirements of moving toward a low carbon economy in the OECD countries would rise from about £50 billion per year in ten years time to over £80 billion per year in 20 years time; the corresponding estimates for developing countries are £25 billion rising to £120 billion per year. (Estimates rounded.) These are of course substantial requirements, but turn out to be a modest percentage of the turnover of the industry, ~5% over the next 20 years and ~10% in the longer term. As discussed in Part 3, they could be levered by policies that would not need to be draconian or disruptive to energy supplies.

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[20] The area above the curve in Chris Taylor's chart and a horizontal line representing the costs without innovation.

PART 3: POLICIES AND FINANCE

3.1 Introduction

Parts 1 and 2 sought to show that carbon abatement policies can be based on the knowledge a low-carbon energy system is technologically and economically feasible:

- *A broad portfolio of technological options is available*—for improving efficiency in energy supply and use, and for supplying energy in ways that would lead to low net emissions of greenhouse gases to the atmosphere.

- *The costs of the options are already not far removed from those of using fossil fuels today*. Although their unit costs are presently high, low carbon technologies would initially account for only a small share of supplies. As their share in output rises, unit costs should fall with innovation and with the scale economies in batch production and the provision of supporting infrastructure.

Energy policies in OECD countries have been aiming to broaden the portfolio of technological options and encourage innovation for some time. In both respects they have not been unsuccessful; the technologies have been shown to 'work' and unit costs more than halved in the past 15 years.[21] But national policies throughout the OECD still fall short of what is required; and there is the need to engage developing countries more extensively in the development and use of low-carbon technologies. These are the subjects of this part of the paper.

National policies hold the key to raising the financial resources required. They raise the returns to investments in low-carbon options (a) by raising the price of carbon and thus the prices of the outputs of the fossil fuel technologies with which they have to compete, (b) by directly raising the prices paid for their outputs (for example through feed-in tariffs or through regulatory standards and obligations), and (c) by reducing private costs through tax, capital grant and procurement policies. A few countries have opted (a), but most have favoured (b) and (c) or a combination of the three.

At the international level, disputes over the Kyoto targets have led to an oversight, and thus to an omission on the policy scene, which is that many countries that have rejected the targets, including a large number of developing countries and the US, are developing and using low carbon technologies and practices on an increasing scale, supported by policies to this end. Their reasons are varied and complex, some more to do with energy security than with climate change. Whatever the reasons, however, there is an opportunity to move forward by focussing international agreements and policies directly on technology development and use, facilitated, in the case of developing countries, by an expanded programme of international assistance, on the lines of the recent *Investment Framework* proposed by the World Bank, discussed below. As with other programmes of international assistance, direct investments need to be coupled with the development of national energy policies—in the developing no less than in the OECD economies.

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[21] A good compendium of evidence is to be found in the UNDP/WEC World Energy Assessment (2000).

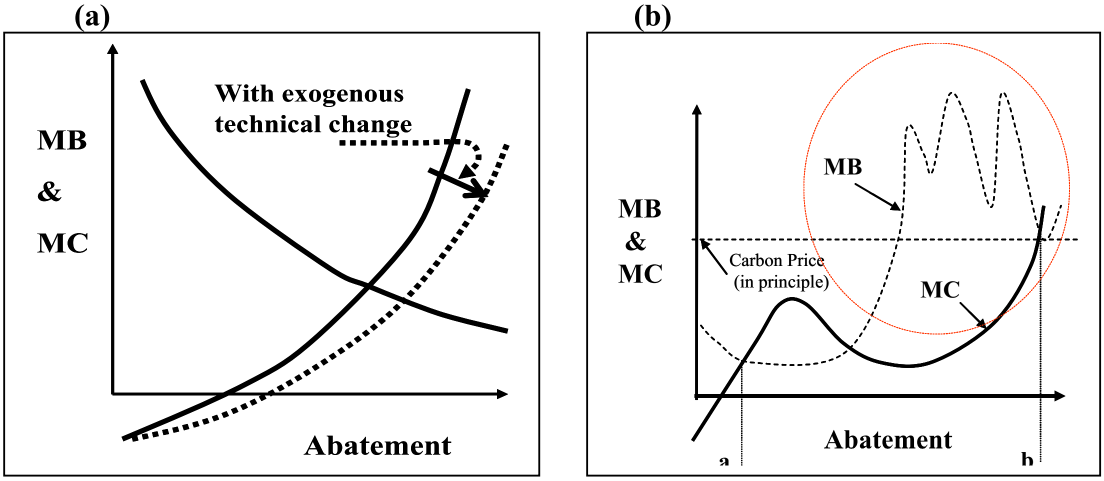
3.2 Issues Regarding Current Estimates of the Benefits and Costs of Carbon Abatement

In an endeavour to find an optimal policy, economists usually seek to estimate curves representing the marginal benefits and the marginal costs of abating greenhouse gas accumulations, with the point of intersection providing the basis for an optimum policy. This characterisation of the problem is however too simplistic—and the estimates of the marginal costs and benefits of abatement that have emerged from it are too unreliable—to provide such a basis. For example, a recent review of published estimates of the marginal benefits finds the mode of the estimates of the damage costs to be $5/ton of carbon, the mean $104/ton, and the 95 percentile $446/ton, but then (incredibly) concludes that the marginal costs of damage are unlikely to exceed $50/ton.[22] There are several issues, of which just two are:

- A large number of studies neglect the possibilities of disruptive changes or threshold effects arising, for example, from the thawing of the permafrost (with attendant methane releases), a loss of glaciers and icecaps, shifts in the Gulf Stream, and damages to the tropical forests. Hence there is a downward bias in the distribution of available estimates;

- The marginal benefit curve is unlikely to take the form of a simple monotonically declining function. Low levels of abatement would do little to stem the dangers of threshold effects, so the marginal benefits would be low; but high levels of abatement would give rise to high marginal benefits if the latter dangers are avoided, such that the MB cure may rise not fall. The possibilities are contrasted with the traditional economic view in Figures 3.1a and b.

Figure 3.1: Marginal Benefit and Cost Curves: (a) the Traditional Economic View and (b) With Endogenous Technical Change and Climate Threshold Effects:



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[22] RS Tol "The marginal costs of carbon dioxide emissions: an assessment of the uncertainties" Centre for Marine and Climate Research, Hamburg University. Working Paper FNU-19, April 10, 2003

Nor is the marginal cost curve likely to be a simple monotonically rising function of abatement that shifts downwards over time exogenously with technical progress, as depicted in the traditional view Figure 3a. Costs do not decline simply with the 'passage of time' but with human effort, imagination and investment, and are better thought of as changing endogenously with the effort and investment put into abatement. The MC curve is more likely to rise at first as the 'easy' options for abatement are taken up, peak and decline as various obstacles (such as the need to develop storage technologies and the hydrogen option) are encountered and addressed, and rise again at very high levels of abatement. MC curves such as the one illustrated in Figure 3b are easily derived using models of endogenous technical change drawing on engineering and economic data[23]; it is even possible for the MC curve to dip below the horizontal axis, depending on the rate of innovation and future oil and gas prices.

The views of economists taking a sceptical position on climate seem to lie somewhere around the intersection at *a* in Figure 3.1b, where the possibility of threshold effects are ignored, and there is the tacit assumption that to go beyond this point would be too costly. Others (including the present writer) are closer to the intersection at *b* on Figure 3.1b, where threshold effects are thought likely and where, with discovery and innovation, the costs of abatement will not be prohibitive. There is a large area (circled in red in Figure 3.1b) where enough is known to decide *whether* to go ahead with policies, but not enough is known to say what the optimum carbon price is or should be.

In this situation a practical approach to policymaking is to analyse policies in terms of their cost-efficiency for working toward a defined goal, for example of stabilising greenhouse gas accumulations at a level indicated by scientific research on the impacts of climate change. In this approach the key insight of economic analysis, the polluter pays principle, remains in tact, but instead of the price required to abate pollution being based on an unknown—and therefore arbitrarily chosen—point of intersection between the marginal benefits and cost curves, it is estimated by reference to the estimated costs of working toward a long term stabilisation target for carbon accumulations. This is also the direction in which current policies are headed.

3.3 National Policies

(a) Carbon Pricing and it Surrogates

The case for favouring the development of low carbon technologies is accepted in all OECD and several developing countries, but few have pursued a policy of pricing carbon directly. Instead they have preferred to introduce tax, regulatory and other incentives to support innovation and the use of 'near-to-market' technologies. When stated in terms of their imputed costs per ton of carbon emissions avoided, the incentives have been substantial. For example:

- The UK Renewables Obligation has a buy-out price of 3p/kWh, but a value of around 4.5p/kWh after including the revenues recycled from buy-out payments. The former (taking this as an indication of the minimum the government thought

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[23] Anderson and Winne (forthcoming).

necessary to stimulate investment) is equivalent to a carbon price incentive of £100/ton on generation from coal and £270/ton on generation from natural gas, which has twice the calorific value of coal and a smaller carbon fraction per unit of energy produced.

- The 30p/litre fuel duty allowance for bioethanol in the UK is equivalent to £150-300/ton of carbon saved depending on the crop and transformation pathway. This is soon to be increased by 15p/litre under the Renewable Transport Fuel Obligation, providing an overall incentive of £225-450/tonC.

- To keep the nuclear option open the UK non-fossil fuel obligation (NFFO) in the 1990s injected approximately £8 billion into the nuclear power industry. On an annualised basis over the remaining lifetimes of the nuclear plants (which had already been subsidised out of electricity tariffs during construction) this amounted to approximately 2p/kWh, or £180/tonC relative to gas-fired generation, the 'fuel of choice' in the 1990s. In addition, Sizewell B went ahead, with an imputed value of carbon of ≈ £250/ton (Pearson and Pena, 1999).

In Europe[24], the incentives for low carbon technologies are of similar orders. Germany's feed-in tariffs for biomass are 8.5-10 €cents/kWh, and for wind 6-9 €cents/kWh, guaranteed for 20 years, with the higher incentive applying to offshore wind projects. In Holland they are 7.8 and 9.7 €cents/kWh for onshore and offshore wind respectively, and in Austria 4-12 €cents/kWh for heat and electricity from biomass, depending on the primary source of fuel. The Scandinavian countries provide a similarly wide range of incentives for biofuels for heat and power and for wind energy, and include a carbon tax in Sweden. Spain's incentives consist of high feed-in tariffs plus 'bonus prices' totalling about 9 €cents/kWh for biomass and wind, and 10-30 €cents/kWh for solar.

The *net* incentives provided for low carbon technologies in European countries, assuming a cost of generation from fossil fuels of 4 €cents/kWh, thus average about 4 €cents/kWh (2.8p/kWh) for wind, are somewhat higher for biomass and much higher for solar. For wind and biomass they are equivalent to carbon taxes of about £100/ton carbon if coal is the marker and £250/ton if gas is the marker, but are appreciably higher for technologies in their earlier phases of development. The same can be said of incentives for solar energy in Japan. Incentives for wind, biofuels and solar energy in the US vary greatly between States. There is a Federal tax incentive of $0.5 per gallon for bioethanol (equivalent to £85/tonC[25]) and up to $1.0 per gallon for biodiesel from waste oils (£170/tonC); both wind and solar energy also receive substantial incentives in the form of capital grants, tax credits and higher prices under the influence of the Renewables Portfolio Standards in effect in twenty States.[26]

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[24] See the "Review of Renewable Energy Development in Europe and the US" by Stenzel, Foxon and Gross. ICCEPT (2003), on which the figures in this paragraph are based.

[25] Here and elsewhere a ppp exchange rate of $1.6/£ is used.

[26] The imputed prices of the RPS schemes are difficult to estimate, but as Chris Taylor commented one might infer them from a comparison of the costs of the technologies so supported with those of the marker technologies. (See next paragraph.)

Comparisons of the costs of the technologies with those of the fuel of choice or 'marker' technologies show why the incentives indeed need to be in the £100-300/tonC range and above if the low carbon options are to be taken up. The first column of Table 3.1 shows the costs of the marker technologies—coal and gas for electricity generation, oil for transport, and gas for heat—to which is added, in the second column, a price of carbon of £250/tonC for the medium term (next ten years) and £150/tonC for the longer term (20 years). The third column shows the costs of the low carbon alternative[27], and the last column the percentage effects on relative costs. The main points are:

- A high price incentive is needed to encourage the emergence of a broad portfolio of options. This could take the form of a carbon tax, the surrogates mentioned above, or a combination of the two (the policies which many countries seem to prefer);
- The incentive can be reduced over time as costs decline with innovation;
- The incentives per ton of carbon abatement need to be much higher than the average costs of carbon abatement discussed in Part 2, which were £145 and £80 per ton of carbon abated for the same points in time. The marginal costs are almost twice the average costs of abatement.

Such estimates, however, vary greatly with the prices of the carbon fuels themselves—particularly of oil and natural gas, which are more volatile than those of coal. The estimates in Table 3.1 assume an oil price of $50/barrel and a gas price of £4/GJ (approximately £4/MBtu), both of which are high by historical standards. If they were to revert to the levels obtaining only 3 years ago, of $30/barrel and £2.5/GJ, or less, the portfolio of low carbon technologies, given a £250/ton incentive, would narrow appreciably to one or two options that would by themselves be too restricted to address the climate change problem—nuclear power and onshore wind (with backup capacity) for base load electricity generation, and electricity generation from coal or gas with carbon capture and storage. Conversely, persistently high oil and gas prices would argue for lower incentives.

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[27] These are the estimates reviewed in my previous paper.

Table 3.1: Effects of Carbon Prices of £250 and £150/tonC on Relative Costs

Low Carbon Technology	Marker Tech-nology	Cost unit	Cost of Marker	Cost of Marker + Carbon Price	Cost of Low Carbon Tech-nology	Net cost, % Marker (incl. cbn. price)
Medium term estimates (10 years). £250/ton C carbon price.						
……….……………………… **Electricity Markets** ………………………...						
Electricity from gas with CCS	NG or coal	p/kWh	2.6	6.2	4.8	-23
Electricity from coal with CCS	NG or coal	p/kWh	2.6	6.2	4.3	-31
Nuclear power	NG or coal	p/kWh	2.6	6.2	3.9	-37
Electricity from energy crops	NG or coal	p/kWh	2.6	6.2	6.3	2
Electricity from organic wastes	NG or coal	p/kWh	2.6	6.2	6.9	12
Onshore wind	NG or coal	p/kWh	2.6	6.2	4.7	-24
Offshore wind	NG or coal	p/kWh	2.6	6.2	6.8	11
Solar thermal (v, sunny regions)	NG or coal	p/kWh	2.6	6.2	11.7	90
PV: distribtd generatn (sunny regions)	Grid elcty	p/kWh	7.9	10.7	18.0	69
dCHP: H from NG or coal + CCS	Grid elcty	p/kWh	7.9	10.7	20.6	93
…………………………………… **Gas Markets** …………………………………..						
Hydrogen: NG or coal + CCS--industry	NG	£/GJ	4.0	7.6	7.7	1
Hydrogen: NG or coal + CCS--distribtd	NG	£/GJ	6.0	9.6	4.2	-56
Electrolytic hydrogen--industry	NG	£/GJ	4.0	7.6	19.7	159
Electrolytic hydrogen--distributed	NG	£/GJ	6.0	9.6	27.1	182
Biomass for heat--distributed	NG	£/GJ	6.0	9.6	9.4	-2
……………………….. **Transport Markets** …………………………..						
Bioethanol	Petrol	p/litre	29.5	75.5	28.4	-62
Biodiesel	Diesel	p/litre	29.5	75.5	47.3	-37
Hydrogen ICE vehicle--fossil H + CCS	Petrol	p/litre	29.5	75.5	54.2	-28
Longer term estimates (20 years). £150/tonC carbon price.						
…….…………………………. **Electricity Markets** ………………………...						
Electricity from gas with CCS	NG or coal	p/kWh	2.1	5.6	4.5	-20
Electricity from coal with CCS	NG or coal	p/kWh	2.1	5.6	3.8	-33
Nuclear power	NG or coal	p/kWh	2.1	5.6	3.5	-37
Electricity from energy crops	NG or coal	p/kWh	2.1	5.6	4.8	-14
Electricity from organic wastes	NG or coal	p/kWh	2.1	5.6	4.1	-26
Onshore wind	NG or coal	p/kWh	2.1	5.6	3.3	-41
Offshore wind	NG or coal	p/kWh	2.1	5.6	4.5	-20
Solar thermal (v, sunny regions)	NG or coal	p/kWh	2.1	5.6	8.8	57
PV: distribtd generatn (sunny regions)	Grid elcty	p/kWh	7.9	10.7	9.0	-15
dCHP--H from NG or coal with CCS	Grid elcty	p/kWh	7.9	10.7	7.6	-29
…….…………………………. **Gas Markets** …………………………………..						
Hydrogen: NG or coal + CCS--industry	NG	£/GJ	4.0	7.61	6.3	-17
Hydrogen: NG or coal + CCS--distribtd	NG	£/GJ	6.0	9.61	13.1	37
Electrolytic hydrogen--industry	NG	£/GJ	4.0	7.61	14.1	86
Electrolytic hydrogen--distributed	NG	£/GJ	6.0	9.61	20.5	113
Biomass for heat--distributed	NG	£/GJ	6.0	9.61	6.5	-32
……………………….. **Transport Markets** …………………………..						
Bioethanol	Petrol	p/litre	29.5	57.1	31	-46
Biodiesel	Diesel	p/litre	29.5	57.1	45	-21
FC Hydrogen vehicle--fossil H + CCS	Petrol	p/litre	29.5	57.1	22	-62
FC Hydrogen vehicle--electrolytic H	Petrol	p/litre	29.5	57.1	72	26

To provide the incentives for technology development, two alternatives are commonly discussed. The *first* is the 'level-playing-field' or 'technology-neutral' approach, much favoured by economists, which is to provide the same incentive per ton of carbon abated for all technologies, e.g. through a carbon tax or a tradable permit system. Unless the carbon tax is set to the levels discussed above, however, or alternatively unless the availability of permits is restricted such that the carbon price would be bid up to such levels, there is the danger that—admittedly for political rather than economic reasons—carbon prices will be set too low, and lead to too narrow-a-portfolio of options emerging. In other words, the policy could easily regress into to an 'eggs in one basket' policy, and to an increase in the risks of the policies not succeeding. The risks both of climate change, and of developing the technologies needed to mitigate its effects, point to the merits of a diverse portfolio of options being developed. In addition, policies need to take account of the positive externalities of innovation as well as the negative externalities of pollution on which the idea of carbon pricing is based.

Such arguments have given rise to the *second* alternative, which is to combine carbon pricing with incentives to support innovation directly. This is the direction that policies in OECD and developing countries are currently taking. It can be defended by reference to principles of a policy structure that combines:

- Disincentives to invest in polluting technologies with negative externalities, i.e. a carbon tax or tradable permit scheme;
- Positive incentives to invest in technologies for which the positive externalities of innovation are likely to be large.

Both can be designed to include a sharing of the financial risks between industry and government.

(b) Policies in Use

The instruments actually deployed by governments are numerous and bewildering—all the more so because they are frequently amended in complicated ways. They are the outcome of intense lobbying, what is politically possible, and compromises arrived at in the context of local energy market characteristics and regulatory arrangements. The following list is not comprehensive:

- Excise and corporate tax allowances: e.g. reduced taxes on biofuels in the UK and the US; investment tax credits.
- Capital grants for demonstrator projects and programmes: clean coal programmes in the US; PV 'rooftop' programmes in the US, Germany and Japan; investments in marine renewables in the UK and Portugal; and grants for numerous other technologies in their demonstration phase.
- Feed-in tariffs combined with a regulatory incentive to purchase output: wind and PVs in Germany; biofuels and wind in Austria; wind and solar schemes in Spain, supplemented by 'bonus prices'; wind in Holland.

- Quota based schemes: the Renewable Portfolio Standards in twenty US States; the vehicle fleet efficiency standards in California.
- Tradable quotas: the Renewables Obligation and Renewable Transport Fuels Obligation in the UK.
- Tenders for tranches of output with increased output prices subsidised out of the revenues from a general levy on electricity tariffs (the former UK NFFO).
- Government assumption of risks and liabilities: nuclear wastes and decommissioning.
- Cross-subsidy of the infrastructure costs of connecting new technologies to networks.
- Procurement policies of public monopolies. This was the approach historically of the public monopolies in electricity for purchase of nuclear power throughout the OECD; it is currently the approach in China.
- Procurement policies of national and local governments: e.g. demonstrator projects on public buildings; use of fuel cells and solar technologies by defence and aerospace industries; hydrogen fuel cell buses and taxis in cities; energy efficiency in buildings.
- Efficiency standards for building materials and appliances, often supported by tax credits and grants (many countries).
- Tradable carbon-permit schemes: the Nordic countries; the EU's tradable permits, applied to particular sectors.
- Subsidised loans (interest free loans for 'green projects' supported by exemptions from corporate taxes for such operations).
- Carbon taxes: Sweden and Norway.

It is not unusual to find two or more instruments bearing on a particular technology, for example tax concessions on costs combined with price support on output.

There are also some interesting new proposals. For example Dr Helm has proposed a guarantee price for tranches of 'no-carbon generation', to be available for nuclear power, generation from fossil fuels with CCS, all renewable energy forms and decentralised heat and power. This would have the merits of introducing a technology-neutral element into current policies in the UK. It could be financed in one of three ways: out of taxes, a levy on electricity sales (as with the NFFO in the 1990s), or the revenues generated by a buyout price (as with the Renewables Obligation) equal to the guaranteed price. Whichever route is chosen, however, there would still need to be additional incentives for innovation to encourage the development of presently higher cost technologies of long-term promise, as the recent report of the House of Commons Audit Committee rightly noted, as did Dr Helm. [28]

Despite their diversity, the above instruments have one or both of two things in common: one is to reduce the private costs and risks of investment, the other to increase cash flow receipts through price support by regulation, marketable permits, subsidy or public procurement at the higher prices. In short they have raised the private rate of return to investment such that a large number of energy companies and manufacturers have also invested in the development and use of the technologies.

The demerits of such policies compared with the simplicity and efficiency of carbon pricing directly are standard fare in academic and trade journals. Ex post evaluations of experiences with the various instruments should shed further light on their relative efficiency and practical effectiveness. Notwithstanding their well-known economic limitations, the collective outcome across OECD countries has not been unsuccessful in light of the general aim of the need to develop low carbon alternatives to fossil fuels. Substantial financial resources have been mobilised for technology development, and a portfolio of options is now available on a scale that few were able to envision barely 20 years ago (Pacala and Socolow, 2004).

(c) Future Directions for National Policies

Until costs are reduced through innovation price incentives in the range £200-300/tonC abated will be required. If policies were to be based, say, on a carbon tax, the fiscal impact would be appreciable[29], and perhaps for this reason the case for taxing carbon has been eschewed by all but the Scandinavian governments in favour of the technology- or innovation-oriented policies listed above to allow options to be developed, demonstrated and brought into commercial use.[30]

Such policies have an *option value*. When uncertainties are large there is a tension (a) between delaying irreversible investments until the uncertainties are reduced and (b) bringing investments forward to avoid irreversible damages.[31] With respect to the technologies for mitigating climate change, however, there is a third factor to take into account, which is (c) the option value of discovery and innovation: options do not emerge exogenously, but require investments in R&D and commercial demonstration to reduce costs and risks. Papathanasiou (2001 and 2005) has shown that (b) and (c) can be large in relation to available estimates of (a), and that the wider the greater the uncertainties ahead, the more robust is a policy to broaden the range of options available becomes.

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[28] *Keeping the Lights on: Nuclear, Renewables and Climate Change* (2006, p51). Sixth Report of the Session 2005-06. Dr Helm's testimony is summarized in this report.

[29] E.g. a tax of £200/ton would raise £40 billion per year in the UK, and $2.5 trillion per year worldwide.

[30] The small effects on taxes and energy prices so far are largely due to the energy market shares of the technologies being small—around 8% in the case of nuclear, where new investment has been very low, and perhaps 2-3% for the new renewable energy technologies.

[31] Dixit and Pindyck (1994).

Being replete with political compromises policies that have emerged so far are rarely intellectually pleasing. But they have had the merits of (a) being implemented in times when controversies over the science of climate change, and over the technologies to abate it, threatened the even worse outcome of paralysis; and (b) having had the practical effects noted above—operating experience has been gained, unit costs have declined, conversion efficiencies have improved and investment has increased.[32]

Since market liberalisation 15 years ago, most OECD countries are in their third phase of defining policies. As with the UK's aspirations beyond 2015 further phases are likely to follow. From an economic perspective there needs to be two elements to future policies:

1. *Pricing carbon directly*. With the hardening of evidence on climate change the case for a transition to full-blown policies involving the pricing of carbon directly becomes stronger. The two main possibilities are carbon taxes and marketable permits.

The economist's case for carbon taxes remains sound, notwithstanding the reluctance of governments to accept it. It has been made many times, and it is unnecessary to rehearse the arguments again here. Innovation may further help to win the case politically by reducing the scale of the carbon tax required to encourage substitution.

Marketable permits are winning acceptance, though there are dangers that the allocations of permits or quotas will be politically manipulated, as happened with National Allocation Plans (NAPs) in the EU tradable permit scheme. The scheme is currently confined to electricity generation though there are plans to include other sectors such as transport and the chemical and aluminium industries by 2008. Volatility is another issue, and also not unconnected with politics. The spot price in April 2006 was € 28/ton CO_2, or € 100/tonC, an appreciable incentive, but had dropped by half less than six months later.

Another danger is that as its scope expands its administrative requirements the possibilities for further political manipulation and price volatility will increase. It is a standard observation in economic texts that tradable permit schemes are best applied when there are a few well-organised participants, as was the case for trading in leaded fuel allocations in the US refineries in the 1970s (Hahn 1989), and with sulphur trading in electricity generation in the 1990s (Joskow et al, 1999). For the use of hydrocarbon fuels the diversity and number of participants in the energy market will inevitably set limits to what tradable permits might accomplish.

2. *Policies to support public and private R&D and innovation*. R&D efforts declined 10-fold in the UK over the past 25 years, 4-fold in the US, and 2-fold on average in the OECD countries (see Annex 7), a period when R&D expenditures in other sectors of the economy increased substantially. There were three reasons:

- Concerns in the period 1973-85 about energy security in oil importing countries abated following the collapse of oil prices in the mid' 1980s, and were mirrored in a relaxation of the R&D effort. Such concerns have only recently resurfaced;

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[32] UNDP/WEC World Energy Assessment (2000), ICEPT (2002, and several publications by IIASA and the IEA provide reviews and evidence on unit costs.

- Discouragement with nuclear power, which had taken the lion's share of the budgets;
- With the liberalization of energy markets in the 1990s, competitive forces shifted the focus from long-term investments such as R&D towards the utilization of well-developed technologies and resources—of natural gas for electricity generation and heat in particular.

The task of mitigating climate change means that the R&D effort needs to be ramped up once again, perhaps to or above the levels that existed a generation ago. The challenges facing the energy sector today are far more demanding than they were then, and a much broader portfolio of low carbon technologies and practices needs to be developed further.

In the UK the establishment of the Energy Research Centre (UKERC) and the announcement of the formation of new public-private National Institute of Energy Technologies are recent initiatives to restore R&D. The US is also to increase its Federal energy R&D budget (it is already 60 times that of the UK).

Most of the policies listed earlier have an element in them to foster innovation. However, they frequently confound the aims of innovation policies with the aims of carbon pricing, which are to encourage the use of technologies that have already passed through their RD&D and commercial trial stages. For example the UK Renewables Obligation provides the same incentive for onshore wind, a mature technology, as for offshore wind, despite the far greater engineering challenges facing the latter and the greater scope for reducing costs. The support offered needs to vary with the phase of development a technology—a policy that was called 'banding' in the former UK NFFO scheme.

The elements of innovation policy have been outlined in several recent studies:[33]

- An increase of R&D in public research establishments;
- capital grant and tax credit schemes for private R&D, demonstration and early commercialisation projects;
- public procurement policies;
- 'backloading' support (use of awards) for innovation;
- setting technology standards and goals;
- investment in science and engineering education.

By facilitating invention and reducing costs, such policies complement the pricing of carbon directly, and should pave the way to lower carbon prices in the long-term.

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[33] See Anderson, Clark, Foxon, Gross and Jacobs (2001) financed by the ESRC's former Global Environmental Change Programme. Also US Technology and Innovation Policies: Lessons for Climate Change. A report by the Pew Centre for Global Climate Change *by John A. Alic, David C. Mowery* and *Edward S. Rubin. November 2003*

3.4 International Policies

Future international policies need to be based on two sets of assumptions, one financial, one institutional.

The financial assumption is that the bulk of the finance required for investment will need to be generated through the incentives provided by national policies, in both the developing and the OECD economies. There is of course a convincing case for increasing the financial assistance to developing countries in this area, which has been set out in the recent World Bank Report, *Clean Energy and Development: Toward an Investment Framework* (2006). But the scale of the finance required is well beyond that proposed under this framework, which will necessarily be confined to a facilitating role.

The institutional assumption is that the organizations are already in place to provide the assistance if the financial resources are made available. They will of course need to organize themselves for the effort. But with this qualification, the institutional basis already exists for the implementation of international policies.

There is also an institutional base to build on in developing countries, many of which already support the use of low carbon technologies.[34] The Global Environment Facility already has a portfolio of approximately $12 billion (including levered finance) in energy efficiency and renewable energy projects, and further investments are emerging under the CDM. Hence there is a willingness in developing countries to participate in the kinds of investment that will reduce carbon emissions—even though they have rejected the Kyoto targets. To varying degrees therefore, the 'host' institutions to implement the required policies are also in place, in the form of energy market regulatory arrangements, administrative systems capable of taxing or otherwise pricing pollution, research establishments, a capacity to develop supporting infrastructure and departments to monitor and oversee policies.

The two assumptions together suggest that future negotiations on climate change could progress by focusing less on country emissions targets, which have not been widely accepted, and more on agreements to promote the use of non-carbon technologies and practices directly, and allowing countries flexibility in the choice of instruments.[35] China and India for example, have rejected the Kyoto emissions targets, yet have commitments to the development and use of low carbon technologies that are more ambitious than many of the countries that have signed up to Kyoto. (Indeed the same can be said of the United States.)

(a) Financial Requirements

In developing countries—as in the OECD countries—the aggregate investment requirements of addressing climate change are likely to rise to a hundred billion dollars per year or more over the next generation. It is unlikely that resources of this magnitude

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[34] Renewable Energy Policy Network, (2005)

[35] A number of people have suggested this, e.g. Barrett (2004), Schelling (2002) and Papathanasiou and Anderson (2001).

could be provided through international assistance alone. The key must be to find policies that will raise a substantial portion of the financial resources in the countries themselves, through policies to support the development and use of low carbon technologies. Developing countries are not unwilling to go down this route, even if, as in the OECD countries, they are motivated by issues of energy security as much as any other factor.

The estimates in table 3.2 are those derived in Part 2 above, but put in the context of the of energy demand growth in the OECD and developing countries. They show the likely expenditures of consumers on energy supply, and the expenditures that would be required to achieve high levels of carbon abatement. They relate to the 550ppm CO_2-equivalent stabilization target considered in the Stern Review. The estimates for developing countries are for Africa, South and East Asia and Latin America.[36]

Table 3.2: Energy Supply Costs and the Costs of Carbon Abatement

	2005	**2015**	**2025**	**2050**
Primary Energy Demands, Exajoules/year:				
OECD	240	250	260	270
East and South Asia, Latin America and Africa	170	270	420	760
Total	410	520	680	1030
Energy supply costs, £ billion per year @ £6.5/GJ of primary energy:				
OECD	1700	1700	1760	1590
East and South Asia, Latin America and Africa	1200	1850	2800	4470
Total	2900	3550	4560	6060
Carbon emissions without abatement, GTC/year:				
OECD	3.5	3.7	3.8	3.9
East and South Asia, Latin America and Africa	2.5	3.9	6.1	11.2
Total	6.0	7.6	9.9	15.1
Carbon emissions with abatement, GTC/year:				
OECD	3.5	3.3	2.7	1.2
East and South Asia, Latin America and Africa	2.5	3.7	4.6	3.4
Total	6.0	7.0	7.3	4.6
Carbon emissions abated, GTC/year:				
OECD		0.4	1.1	2.8
East and South Asia, Latin America and Africa		0.2	1.5	7.8
Total		0.6	2.6	10.6
Cost of abatement £ billion/year (=cost of abatement per ton C x emissions abated):				
OECD		50	100	170
East and South Asia, Latin America and Africa		30	130	470
Total		80	230	640
Cost of abatement as percentage of energy supply costs without abatement:				
OECD		3	6	10

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[36] Estimates for Russia and the Middle Eastern Oil Exporting Countries are excluded on the grounds that these regions would be financially self-sufficient. The focus here is how to finance climate mitigation in the lower income countries. Estimates of the global financial requirements are presented in Part 2.

East and South Asia, Latin America and Africa		2	5	11
Total		2	5	11
Assumptions:				
Abatement costs, £/tonC	225	145	85	60
Abatement factor, relative to no abatement--OECD	0.00	0.10	0.30	0.70
Abatement factor, relative to no abatement--Developing countries	0.00	0.05	0.25	0.70

The following are the main points:

(i) The demands of the OECD, in the absence of major improvements in energy efficiency, seem set to grow somewhat relative to today's levels, from 200 to around 270 Exajoules (EJ) per year.

(ii) Those for the developing countries in contrast are likely to grow immensely in any scenario of economic success: to double or more from 170 EJ over the next 25 years (the 'medium term' in the table) and double or more again by 2050, with further growth beyond then. Even a quintupling of their demands would leave developing countries with only one-third of the per capita energy consumption of the OECD countries today.

(iii) There are corresponding increases in carbon emissions from developing regions, dampened perhaps by a long-term shift from coal to natural gas for electricity generation and heating. Without carbon abatement policies, global emissions would double in two generations to around 15 Gigatons of carbon per year, excluding emissions from Central Asia and the Middle East. To meet the stabilization target of 550 ppm the Stern Review estimated that carbon emissions from energy production and use would need to be reduced to under 5 GtC per year by 2050, in the face of an enormous growth of world demand for energy.

(iv) The costs of abatement are initially assumed to be £225/tonC, declining initially with innovation to around £85/tonC over the next 20 years and then to £60/tonC in the long term, for reasons discussed above.[37] Under these assumptions the costs to OECD countries would rise to £100 billion per year over the present generation, and to the developing countries to nearly £200 billion per year; in both cases these costs would double over the following generation. Without innovation, the costs would be at least twice these magnitudes.

(v) Enormous though such expenditures would be, they would rise to only 10-12% of total expenditures on energy. In the OECD countries total expenditures on energy are around £1.7 trillion per year today; in developing countries, they are £1.2 trillion per year with the prospect of doubling over the next 25 years and doubling again to over £4 trillion per year by 2050.

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[37] The rapid decline from £200/tonC to £145/tonC and then £85 in the first generation of investments can be defended by reference to the steeply declining costs typically encountered in early phases of deployment; learning curves take the form of $C_t = C_0 (X_t / X_0)^{-b}$, where *C* denotes cost at time *t* and *X* cumulative investment, and b is a parameter. Values of b range from under 0.1 to over 0.3.

On account of the scale of demand growth therefore, roughly two-thirds of the overall net costs of abatement would be incurred by developing countries, and would soon exceed those of the OECD countries, around £130 billion per year in 25 years' time as compared with £100 billion per year in the OECD countries. These estimates assume moderate rates of innovation and that oil and gas prices stabilize at $50/barrel and £4/GJ respectively; increases in the costs of oil and gas would mean lower net costs, as would a higher rate of innovation. A margin of error of ±50%, perhaps more, needs to be attached to the estimates just provided.

How might such expenditures be financed in developing regions? And what institutional arrangements might be needed?

(b) Institutional Arrangements for Finance and Policymaking

There are currently four main sources of international finance: the Global Environment Facility, which amounts to about $0.5 billion per year; bilateral aid; multilateral aid; and the CDM, which may add a further $10 billion per year, though is capable in principle of much further growth. The World Bank's report on a framework for clean energy has proposed an expansion of the GEF plus four further instruments:

- A *Clean energy financing vehicle (CEFV)* to finance high efficiency technologies for mitigating climate change; this would blend grants and carbon finance to buy down the costs and reduce the risks of investment in new technologies and energy infrastructure;
- A *Power rehabilitation financing facility* to enable developing countries to rehabilitate inefficient plants;
- A *Project development fund* to identify and prepare a pipeline of "bankable" projects;
- *Venture capital funds* for promising new and clean energy technologies.

As with the GEF, CDM and bilateral and multilateral aid these would be sources of project finance. The instruments would be able to lever appreciable resources internationally and in the host countries themselves, with a leverage ratio of perhaps 5:1 or more. Their primary roles would be to facilitate investment and policy development, as is the case with international aid more generally. Historically, international aid has financed only a small percentage of domestic investment in developing countries, in the energy as in other sectors; the bulk of investment has been generated domestically. Given the volume of finance required future investment in technologies to mitigate climate change will likewise rest on the willingness of developing countries to introduce policies to support their use.

There are several possibilities for the Stern Report to weigh at the international level:

(i) To support the expansion of facilities established so far such as the GEF (the financing arm of the UNFCCC and UDFCBD) and the CDM.

(ii) To support, in addition, the establishment of the new facilities proposed in the World Bank's Investment Framework. The advantage of these facilities (as with the GEF) is that they would be associated with institutions with over a half-century track record of levering co-finance from multilateral and bilateral aid resources, private capital markets, private industry and the equity contributions of developing countries themselves. A typical leverage ratio is 5:1.

(iii) In addition (a topic not considered in this paper) there is a case for a further facility to be added to the WB's Investment Framework to address the problem of emissions arising from the deforestation, land clearance and land degradation, an issue well-identified by the Stern team.

(iv) To encourage the bilateral and international institutions to promote national policies for the development and use of climate friendly technologies.

China, India and Brazil already have policies to encourage the use of low carbon energy technologies, but there are many other countries too, motivated in part by high and volatile oil prices and energy security. India's interests in both modern and traditional forms of renewable energy are long-standing. Hence—in contrast to the experience with the Kyoto targets—developing countries seem willing to take such policies forward.

(c) International Research and Development

A gap in the financing arrangements at the international level concerns the development and demonstration of new technologies. The Global Environment Facility, its Implementing Agencies and the multi-lateral and bilateral agencies are already involved in the application of *established* low-carbon energy technologies. The GEF alone already has a $15 billion portfolio of investments, including the investments directly levered by GEF grants. But there is a need to press the 'technology frontier' harder and move the technologies forward:

- Low carbon technologies and practices are fertile grounds for discovery and innovation—in biofuels, energy efficiency, PVs, the offshore resource, fuel cells, and hydrogen production, storage and use.
- There are critical constraints to be addressed, especially (but not only) in energy storage technologies for both vehicles and stationary applications.
- The education and training of scientists and engineers. The output of low carbon technologies will need to expand nearly 20-fold over the next 40-50 years, requiring new generations of engineers and scientists to work on energy technology development and use.
- There is the need to involve scientists and engineers from developing countries in the task. Already China and India are each graduating 250,000 engineers and scientists each year—as many as in the US and in the European Union. A rich and copious source of discovery and innovation is emerging in developing regions.

A 20 year programme to support demonstration projects aggregating to perhaps 1-2 GW per year, plus support for involving scientists and engineers from developing regions in the programme, and in more fundamental R&D, would probably cost £3-6 billion per year initially, of which perhaps 50% could be levered through private investment, international offset programmes such as the CDM, and sales of the actual energy produced. The balance of funding would come from expanded R&D budgets and resources allocated to demonstration activities. Higher leverage rates would be achievable as the programme progressed and as conversion efficiencies and confidence in the industry improved. Examples where co-operative endeavours could take investment forward in developing regions include:

- Advanced thermal solar projects;
- Solar home systems, including grid connected PVs;
- Energy efficiency in buildings, transport, commerce and industry;
- Offshore wind, wave and tidal stream projects;
- Multi-purpose projects to restore degraded lands and watersheds, improve the productivity of land, and provide bio-energy and carbon sequestration as a by-product;
- Fuel cells for decentralised electricity supplies and CHP;
- Hydrogen and fuel cells for transport;
- Experiments in hydrogen production, storage and utilization; these to include:
- Hydrogen production from coal and gas with carbon capture and storage.

Such projects would be a complement not a substitute for the much-needed expansion of national programmes discussed in Section 3.3 above. Countries need to commit to expanding their R&D and demonstration efforts in ways that reflect the perceptions and skills of their research communities. The scale and modularity of many options is such that they are often best pursued independently by each country through its research institutions—a policy that should encourage an internationally diverse portfolio of activities. In some areas an international collaborative effort may be needed (as happens with fusion). In others the collaboration may be bilateral or between universities in several countries, drawing on a plethora of channels that have long evolved, often fostered by national academies, societies and foundations.

It is unnecessary to be too prescriptive. The important point is that current efforts need to be ramped up at international as well as national levels, and supportive of what is a rich array of ideas that are already to be found in their research communities.

(d) The Precedent of International Agricultural Research

There is one excellent precedent for such an effort, which agriculture. In the 1950s and 1960s the major concern was how to feed the world given that the scope for increasing agricultural output through land expansion was becoming limited and the world's population was set to double by the end of the century, which of course it did. Hence a big and successful effort was made to improve yields of agriculture research and extension, by bolstering national research stations and a network of international research centres, the latter later brought together under the aegis of the Consultative Group on International Agricultural Research (CGIAR) under the chairmanship of the World Bank. The following extract from the CGIAR history points to an inspirational precedent: [38]

> "The CGIAR grew out of the initial international response to widespread concern in the 1950s, 60s, and early years of the 70s that many developing countries would succumb to famine. A pessimistic forecast of the time predicted vast famines between 1970 and 1985, with "hundreds of millions" starving to death. Such grim predictions were proved wrong by a combination of connected trends: reorientation of domestic policies in developing countries that were considered particularly vulnerable, sharply focused research by developing country scientists, a great effort by developing country farmers, and the impact of international agricultural research on tropical agriculture. …. Unprecedented harvests were recorded in parts of Asia and Latin America, from new varieties of rice, wheat, and maize based on international research. In India, for instance, the … average yield increase for cereals between 1961 and 2000 was 146 percent. .. ."

Energy RD&D of course poses different problems, and requires a different approach. But several lessons from the experience of agriculture are relevant for an international RD&D programme in the development of low carbon technologies. In the case of agriculture:

(i) There was a shared commitment among the sponsors;

(ii) The programme evolved from an already extensive network of national research centres (as would be the case for energy);

(iii) It was based on a real demonstration and R&D projects, and was not simply a 'talking shop';

(iv) The efforts were not centred on one institution in one country, but divided across a set of institutions in several countries specializing on particular crops (rice, wheat, maize, agro-forestry and so forth) and livestock farming;

(v) There were good working links between the international and national centres of RD&D;

(vi) There were also good working links between the programme and the users (extension services and farmers).

In the energy industry there are also precedents to build on, and an institutional base. Perhaps the most prominent example is the ITER project on nuclear fusion. The project is supported by European Union, Japan, China, India, the Republic of Korea, the Russian Federation and the USA. Negotiations took nearly 5 years but the scheme once again proves that large-scale technological cooperation is possible. The EU agreement to develop a near-zero emissions coal plant in China may prove to be another example; it will be the first CCS project sited in a developing country.[39]

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[38] See www.cgiar.org/who/history/index.html

[39] Chris Taylor noted another example in a note for the Stern Review. It is the US-led International Partnership for the Hydrogen Economy, which is based on informal co-operation between several countries. The Partnership was established in 2003 as an international institution to accelerate the

(e) A New Focus for Climate Change Negotiations?

A focus on innovation also offers a way forward for future international negotiations. Some countries may wish to continue with emission targets for national policymaking, and to use them as a vehicle for offset programmes such as the CDM. However, some way of engaging countries that have rejected—and have made clear their intent to continue to reject—the Kyoto Accords and carbon emissions targets needs to be found. Technology development, supported by the sorts of policies discussed earlier, and facilitated by an expanded programme of international assistance, may be the key:

- First, most developing countries, and all countries in the OECD, support policies to encourage the use of energy efficient and renewable energy technologies, and there is interest in China and India in the use of fossil fuels with carbon capture and storage. Thus the approach meets a crucial criterion for negotiations, which is a willingness of countries to participate in the policies discussed.

- Second, there is a well-established set of institutions in place, and significant experience already, for the administration of an expanded programme to facilitate policymaking and investment, in ways that would engage the scientists and engineers of developing countries.

A number of academic studies have independently suggested a focus on technology development.[40] There is a body of professional opinion and writings to draw on for the practical development of the idea.

3.5 Conclusions

The total costs (excluding taxes) of meeting the world's demand for modern energy forms today amount to around £3 trillion per year, of which two thirds are in OECD countries and one third in developing countries. With economic growth they are set to double over the next two generations, the bulk of the increase being in developing regions, in Asia and Latin America in particular. The average costs of addressing climate change may raise the real costs of energy by as much as 10%, depending on future oil and gas prices and the capacity of the research community and industry to reduce costs. Substantial resources will need to be raised therefore to address climate change, perhaps rising to £100 billion per year in the OECD countries over the next 20 years, and £130 billion per year in developing countries.

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development of hydrogen and fuel cell technologies. It provides a forum for advancing policies, and establishing common technical codes and standards; and it educates and informs stakeholders and the general public on the benefits of, and challenges to, establishing the hydrogen economy. The partners include Australia, Brazil, Canada, China, European Commission, France Germany Iceland, India, Italy, Japan, Republic of Korea, New Zealand, Norway, Russian Federation, United Kingdom and United States.

[40] Johanssen et al (1990), the UNDP/WEA World Energy Assessment led by Professor Goldemberg (2000), Barrett (2004), Schelling (2003), the US National Academy of Sciences study (1994) *Marshaling Technology for Development*, and Papathanasiou and Anderson (2001).

Such resources can be generated through national policies to favour the development and use of low-carbon alternatives to fossil fuels. It is worth recalling that energy taxation alone around the world raises resources of five or more times the amounts just noted. Few of course would advocate a 'tax-and-spend' approach to the problem, and instead policies so far have focussed on ways of improving the cash flows of private investments in the alternatives. Three kinds of policies have been pursued, of which the second and third have been the most widely preferred:

1. Pricing carbon directly, as in the Nordic countries and with the EU permit trading scheme;

2. Raising the prices paid for the outputs of low-carbon energy technologies, as with the Renewables Obligation in the UK, the feed-in tariffs in several EU countries, the renewable energy portfolio standards in several US States, and energy efficiency standards in many countries;

3. Reducing the private costs of investment through tax credits; government finance for R&D and demonstration projects; tax credits for the incremental costs of commercialising the technologies; and subsidising the costs of providing supporting infrastructure. (All OECD countries, though to varying degrees.)

Notwithstanding the much-discussed shortcomings in their scale and structure, such policies have several accomplishments to their credit: the portfolio of proven technological options for addressing climate change has widened appreciably, to include the full range of renewable energy and energy-efficient technologies, as well as nuclear power and carbon capture and storage; conversion efficiencies have been improved; costs reduced; and fertile ground for discovery and innovation has been opened up. Furthermore, it has proved politically possible to implement the policies in a period when controversies over the extent and social costs of climate change, and over the technologies for abating it, ran deep (as they still do) and threatened the much worse outcome of paralysis.

***Policies at the national level*:** National policies will inevitably vary between countries, and often between regions within countries, as in the US. This is not only because they will vary with local social and political concerns, lobbying, and what is fiscally and administratively feasible, but because energy markets and regulatory arrangements differ greatly, ranging from high levels of state ownership in some countries to high levels of market liberalisation in others, and many shades in between. As a general rule, economic principles suggest that two categories of instruments will be needed:

(a) A shift toward the pricing of carbon directly;

(b) Incentives for R&D and innovation.

The returns to innovation are likely to be immense. Over the past 15 years, the costs of the low-carbon options have been more than halved; there is no evidence, in fact the opposite, to suggest that the possibilities for cost reduction and efficiency improvements from innovation are exhausted, and even conservative assumptions point to the possibilities of reducing the costs of responding to climate change by several hundred billion pounds per year. There is a debate as to how much innovation would be better stimulated by (a) rather than (b), but most analysis points to the desirability of using both categories of instruments.

Most analysis also points to the desirability of supporting a broad portfolio of technologies. No technology offers a panacea: nuclear power is still limited to base-load electricity production; fossil fuels with carbon capture and storage offer more flexibility, but without developments in hydrogen as a transport fuel and for heating will be limited to the markets for electricity; biofuels can make significant contributions to the markets for transport fuels, heat and electricity, but will eventually be limited by the availability of land; and whilst ‘intermittent’ renewables such as wind, solar, wave and tidal energy are together virtually unlimited in scope, they too will depend on the development of storage or hydrogen-using technologies at high levels of market penetration. In addition, technologies that are more costly today, such as solar energy and decentralised forms of heat and power, hold too much promise to be ignored.

The national policies discussed above can be viewed as practical if second-best surrogates for (a) and (b). They are in a state of flux in all regions, indicating a willingness of many countries, including all the OECD and the majority of developing countries to move forward. New instruments are continually being proposed and existing ones amended, re-formed, or superseded. International exchanges of experiences with policies, such as those provided by the IEA, the GEF and the multi-lateral development institutions will be important for taking the policies forward.

***Policies at the international level*:** Past pre-occupations with reaching international agreements on carbon emission targets have led to a crucial oversight. This is that while the US and developing countries have rejected such agreements, they are willing—and, indeed, in the case of the US, are leading efforts—to develop and use low-carbon technologies and practices. A focus on policies that encourage this is much more likely to meet with agreement.

The investment requirements in developing countries however will be such that, as with conventional aid, resources provided by an expanded programme of international assistance will need to be coupled with those generated by policies in the countries themselves. Five proposals were put forward above:

(i) To support the expansion of facilities established so far such as the GEF and the CDM.

(ii) To support, in addition, the establishment of the new financing facilities proposed in the World Bank’s Investment Framework.

(iii) To add to this Framework a further facility to address the problem of emissions arising from deforestation, land clearance and land degradation.

(iv) To use the finance provided under (i) to (iii) as a means of furthering climate change policies at the national level.

(v) To establish institutional arrangements for involving scientists and engineers from developing regions in R&D and the demonstration of low carbon technologies and practices. Such arrangements were first instituted five decades ago for the green revolution in agriculture, with considerable success.

The international community has been moving in these directions for some years. The GEF and its implementing agencies, for example, already have 15 years of investment experience, and there have been numerous other multilateral and bilateral endeavours. Thanks to national policies so far, and to international investment, albeit on a still minor scale, a portfolio of low carbon technologies is emerging, in developing as in the OECD countries. There is a good technological base, and also a good institutional base, for future policies to build on.

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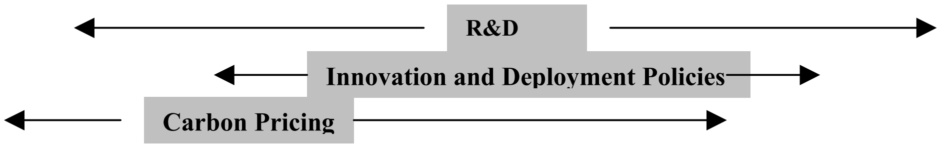
Annex 1: Stage of Development of Low Carbon Technologies

There are many options for mitigating climate change, and it should be possible to meet the world's growing energy demands while moving to an energy system that does not use fossil fuels. Below is a list of some key technologies and practices by stage of development; all the mature and emerging options are available for investment now, and in fact many countries are investing in them. Given the longevity of the current infrastructure the transition could not take place overnight, or even in a few years, but such a transition is possible—at costs that would not be far removed from those of using fossil fuels today.

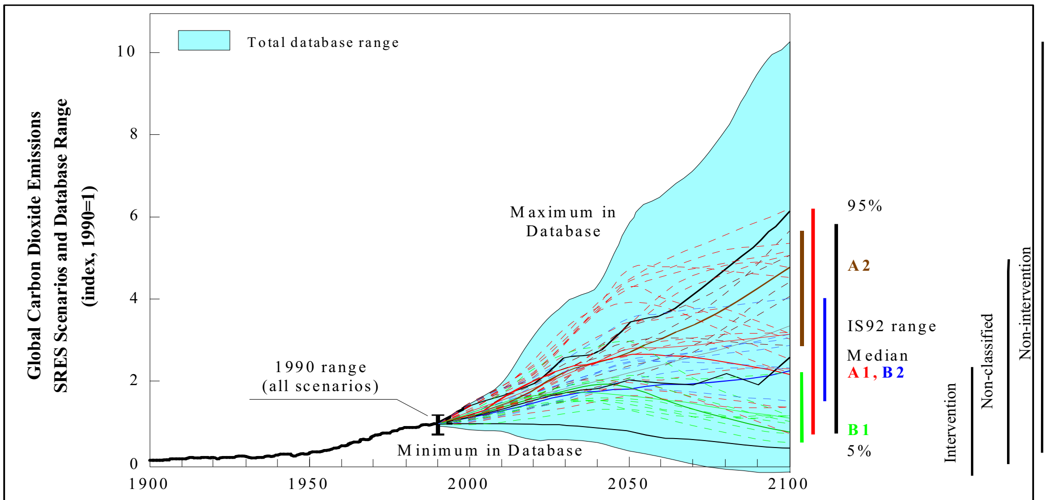
The mature technologies could perhaps take us one quarter of the way to the abatement required by 2050 for climate stabilisation; the mature *plus* the emerging options the full distance. All the mature technologies have limitations: nuclear power, for example, with its confinement to electricity production and with the unresolved problems of waste disposal, decommissioning and proliferation; biomass and wind with the land constraints in some regions; and 'intermittent' forms of renewable energy with the need for storage if they are to achieve high levels of market penetration. The emerging technologies can address these limitations, and create a paradigm shift in energy supply.

Three types of policies are needed to support the transition: (1) *carbon pricing* as an incentive for the mature and emerging technologies to be used; (2) *innovation policies*, such as 'obligations', feed-in tariffs, portfolio standards, and tax credits to encourage investment and innovation in the emerging technologies (and overcome the 'valley of death' promising technologies encounter in the period between R&D and commercial application); and (3) *R&D* in all phases, to find ways of improving mature technologies, and of further developing the emerging and long-term options.

Mature	Emerging: now to c2025	Long-term: experimental
End-use efficiency options in appliances, buildings and transport Nuclear power Onshore wind Large- and small-scale hydro-electricity Biomass (co-firing and CHP) Biofuels for transport Tidal barrages Geothermal Offgrid PV Large- and medium-scale CHP	Ground-source heat pumps Intelligent metering and control technologies Hydrogen production for electricity generation, heat and transport from coal and gas, with carbon capture and storage Offshore wind PV for buildings Thermal solar for power generation Energy from waves and tidal streams Hybrid vehicles Biofuels (ethanol and biodiesel from oil seeds and starchy crops) Fuel cells and small turbines for micro-CHP Synfuel production from coal and gas Energy storage technologies: compressed air; advanced batteries; hydrogen storage… LED lighting	Fusion Advanced fission (breeder and high temperature reactors) Photosynthetic hydrogen

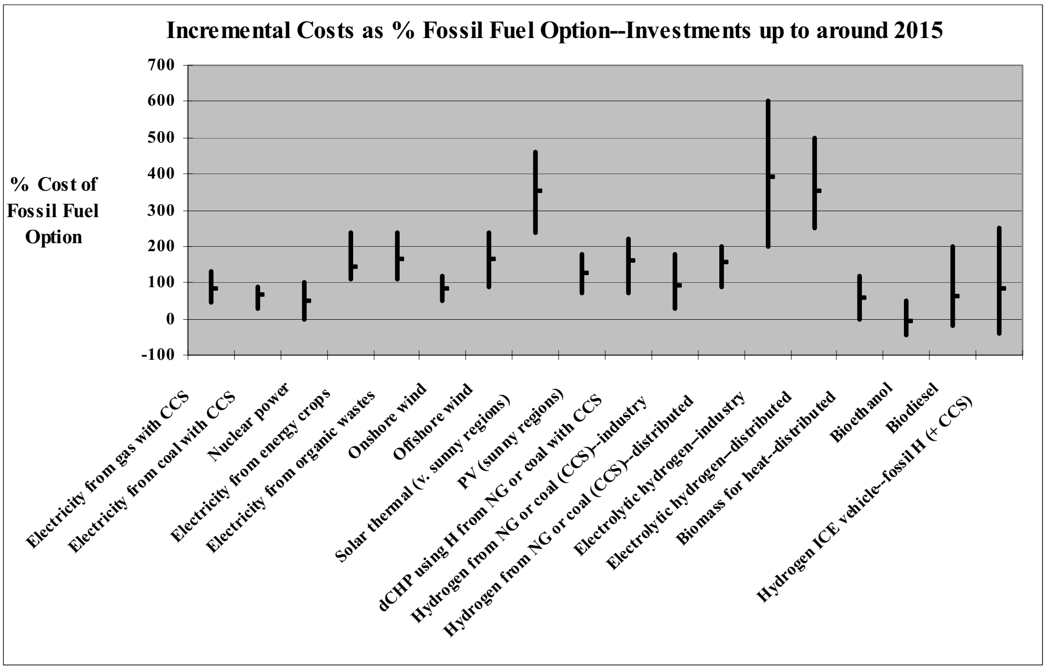


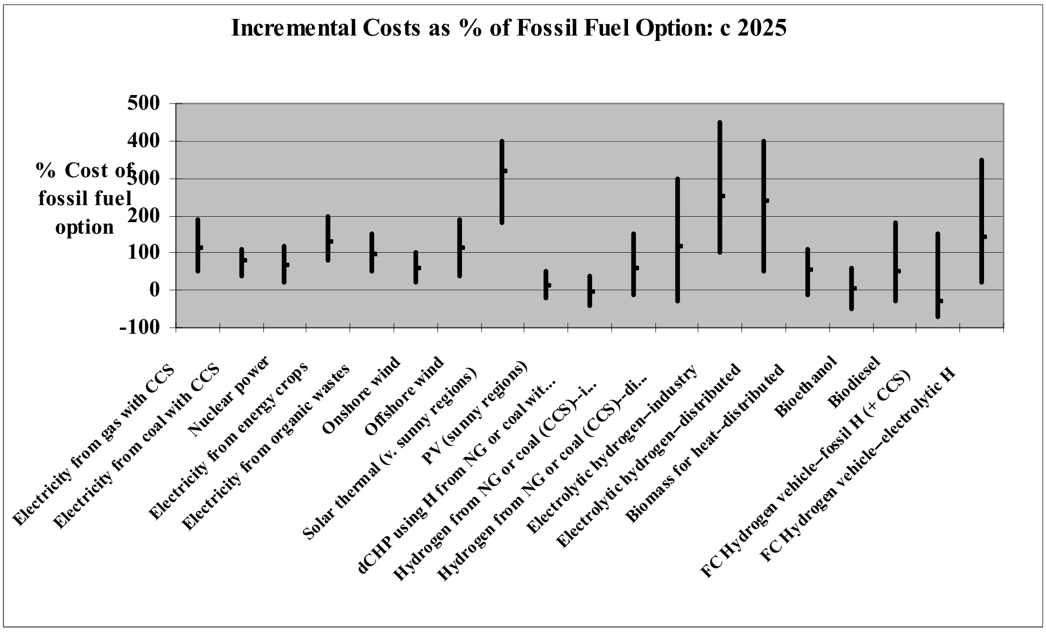
Annex 2: IPCC Scenarios (2000) of Carbon Emissions over the Present Century



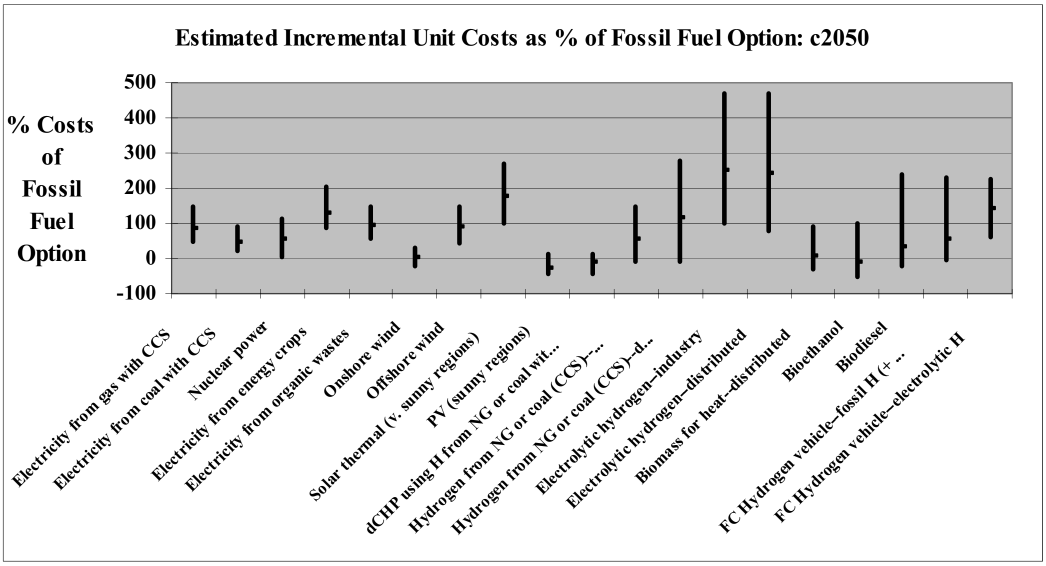
The IPCC scenarios are shown in by the dotted lines: all are consistent with world economic growth rates (in PPP terms) in the range 2.5-3.0% per year. The main feature that distinguishes the high from the low emissions scenarios is technology choice, and (by implication) the policies that bear on it.

Annex 3: Costs of Low Carbon Technologies Relative to Fossil Fuels: Ranges and Means Assumed for the Analysis





Annex 3: continued.



Annex 4. A Comment on the Area Requirements of Renewable Energy

The area requirements of renewable energy differ greatly between technologies, as shown in the following table. Solar energy has the highest yields, being over a hundred times greater than bio-energy and in the tropics ten times greater than the ‘roped in area’ of a wind farm:

	kWh/m2	Tons of oil equivalent primary energy displaced per hectare
Solar: insolation [a/] of 1000kWh/m^2 (typical of UK)	100	250
Solar: insolation [a/] of 2000kWh/m^2 (typical for developing countries)	200	500
Wind: 30% capacity factor, 8 MW/km^2 [b/]	20	50
Bioenergy for heat or electricity (30% conversion factor)	1.5	4
Bioethanol	2.5-3.5	2-3

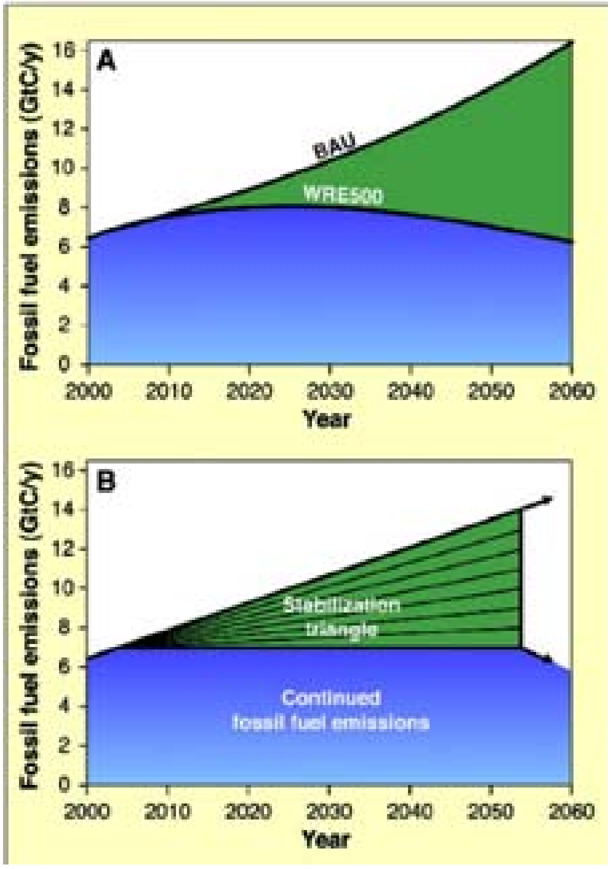
a/ The conversion efficiencies for solar PVs are now around 15% and for solar-thermal power plant potentially higher than this. The above estimates assume 10%.

b/ This is the ‘roped in’ area of a wind turbine array of 5-10MW, which is about one square km. This estimate assumes a capacity factor of 30%; for offshore farms capacity factors are likely to be 40% or higher.

The disadvantages of the relatively low yields of biomass can be offset by several crucially important advantages. First, like fossil fuels, it provides energy in a storable form, with an energy density similar to that of oil fuels, and can be used for power generation, heat supply as well as transport. Second, organic wastes can be used, and in this case the area requirements can be negative in the sense that they reduce the amount of land required for landfill. Third, over large areas of the developing world woody crops can be grown in ways that would enable watersheds and degraded agricultural lands to be restored, for example in a practice known as agro-forestry. This reduces run-off of rainwater; improves micro-climates, soil moisture retention and the supply of nutrients (mulch); and for all these reasons can actually improve the yields of agriculture.

Taken together, renewable energy is a very abundant resource, and capable of meeting the world energy demands many times over. For example, India’s current primary energy demands are approaching 400 million tonnes of oil equivalent per year, which is equal to the primary energy yield of 8 thousand sq km of solar farms—or 0.25% of India’s land area, which is 3.3 million sq km. Such estimates need adjusting for conversion efficiencies (e.g. to hydrogen for transport fuels) and to allow for the point that solar energy conversion is already in a final energy form; but they convey a general point. The conversion efficiencies of all renewable energy technologies are also improving over time with research and innovation.

Annex 5: The 'Stabilization Wedges' of Pacala and Socolow

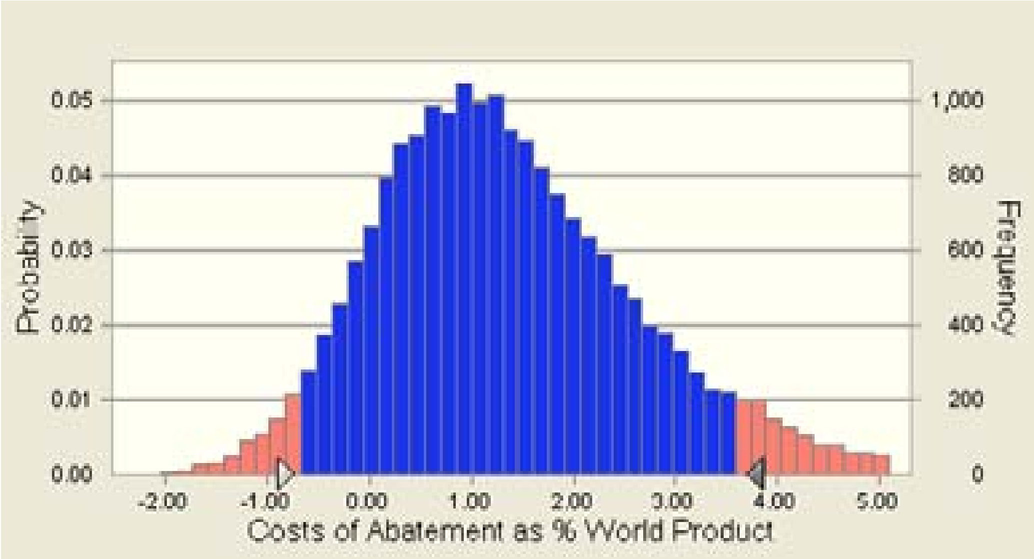


Notes:

Starting from a scenario in which carbon emissions double from nearly 7 gigatons (GtC) per year today to 14 GtC by 2050, Pacala and Socolow consider the possibilities for reducing world carbon emissions by 7 gigatons (GtC) per year by 2050, to bring the emissions trajectory to "a CO_2 emissions path consistent with atmospheric CO_2 stabilization at 500ppm by 2125." As a pedagogical device to illustrate the technologies available (see Figure 4 attached), they break the 7 gigatons reduction down into seven 'wedges', each rising linearly from 0.0 GtC) of abatement in 2004 to 1.0 GtC in 2050. Each wedge is about 60EJ (about 1.3 billion tonnes of oil equivalent or 14% of world primary energy consumption today).

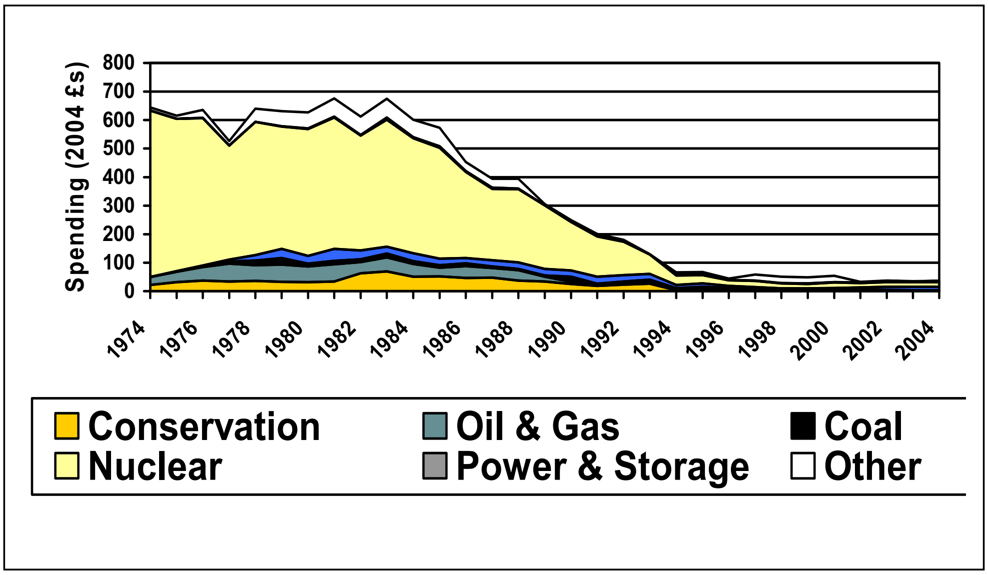
They argue that there are at least *fifteen* technologically plausible ways for producing a wedge based on options "that are already deployed on an industrial scale and that could be scaled up further to produce at least one wedge. [Furthermore,] several options could be scaled up to at least two or more wedges…" The calculations allow for interactions: "emissions cannot be reduced twice… The more the electricity system becomes decarbonised, for example, the less available savings from greater efficiency in electricity uses, and vice versa."

Annex 6: Abatement Costs as a Percentage of World Product When Incremental Costs of Vehicles are included: Monte Carlo Results for 2050

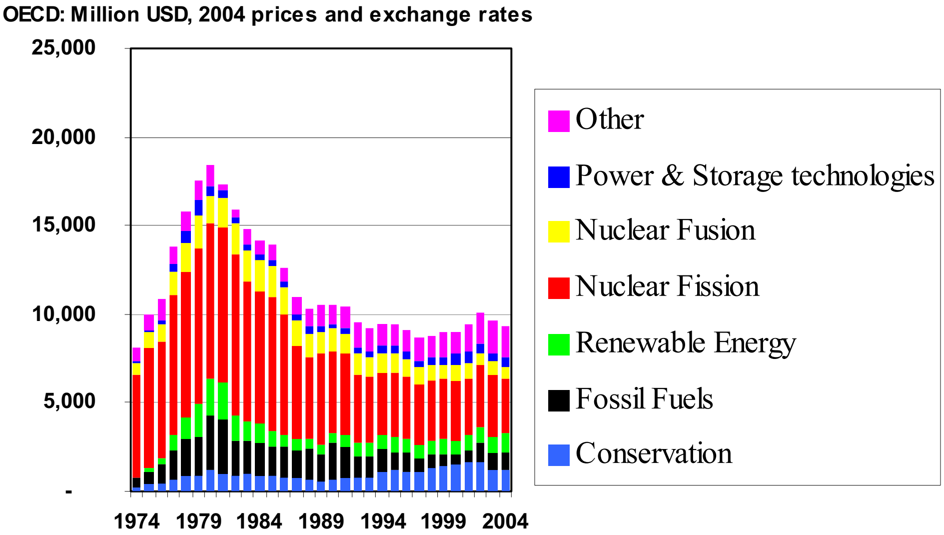


Annex 7: UK and OECD Government R&D Spending since the 1970s

UK Government R & D Spending



Source: Jim Watson SPRU (2006) based on IEA annual data



International Energy Agency

Source: Presentation by Jim Watson to the Stern Review Team