An economic perspective on technological transitions related to energy and climate change

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ABSTRACT

The paper discusses the concept of technological transitions and theories of how they might come about. It then relates this concept to current policy concerns about climate change and energy and presents research results about what a low-carbon energy system might look like and how it could be achieved. It then briefly explores the possible macro-economic costs of moving to a low-carbon energy system.

Technological transitions are relevant to climate change and energy because the energy system is a major technological system in society, and to reduce its carbon emissions dramatically, as is required if dangerous anthropogenic climate change is to be avoided, will require a full technological transition. There are many low-carbon technologies with the potential for large-scale deployment. Simulations suggest that the decarbonisation of the electricity system, involving any or all of carbon capture and storage, nuclear power and renewables, with increasing use of electricity in the residential and transport sectors, will be required. There may also be a role for bioenergy and hydrogen.

In all cases strong public policies will be required to achieve large cuts in carbon emissions, involving carbon pricing, technology support and removing barriers to lifestyle and behaviour changes. Currently, while many different policies have been implemented, they have not been strongly enough applied to achieve sustained emissions reduction. Most models suggest that the macroeconomic costs of substantial cuts in carbon emissions are relatively small (1-4% GDP by 2050) compared to the costs of unabated climate change. However, the political costs of implementing the required policies may mean that politicians are unable in practice to prevent runaway climate change.

1. INTRODUCTION

The most recent climate science suggests that, to have a reasonable chance of keeping average global warming at or below 2^{o}C, which is the target towards which European Union (EU) climate policy is directed, global greenhouse gas emissions will have to peak between 2015 and 2020, and fall by up to 5% per annum thereafter, compared with a long-term average increase in carbon emissions of 2% per annum (ISC 2009, pp.19, 11).

Given the fundamental part played in the global economy by carbon-based fossil fuels, the scale of such a change indicates that what seems to be envisaged is what the innovation literature calls ‘a technological transition’. This paper begins with a review of a number of theories of innovation and technological transitions (Section 2), followed by some discussion of the kinds of technologies that might be involved in such a transition, and some projections for the UK economy of what such a transition for its energy system might look like and some of the policy implications (Section 3). The paper then explores the possible costs involved in this kind of transition (Section 4), before coming to some general conclusions.

2. THEORIES OF INNOVATION AND TECHNOLOGICAL TRANSITIONS

Core to the concept of innovation is change, most importantly technological change. Following Schumpeter (1942), the process of technological change is typically broken down into the following three stages:

- invention – i.e. the first development of a scientifically or technically new product or process;
- innovation – i.e. the commercialization of the new product or process;
- diffusion – i.e. the adoption of the product or process by firms and individuals.

However, technologies do not exist, and new industries and technologies, are not developed in a vacuum. They are a product of the social and economic context in which they were developed and which they subsequently help to shape. Over time, processes of innovation may lead to profound transformation of both the technologies in use and the social context in which they are embedded. These transformations are often referred to in the literature as ‘technological transitions’, a term which implies much more than the substitution of one artefact for another. It connotes a change from one techno-socio-economic system (or ‘socio-technical configuration’ as it is called below) to another, in a complex and pervasive series of processes that may leave little of society unaffected.

There is now an enormous literature on technological change and the broader concept of technological transition (a significant portion of this literature is reviewed in Geels 2002a), only certain elements of which can be highlighted here.

2.0 Technology Readiness Levels

A static view of different stages of innovation is given by the concept of 'Technology Readiness Levels', which is being increasingly used to identify the stage of innovation at which funding is being applied. There are 9 Technology Readiness Levels, ranging from 1 (basic research) to 9 (early deployment of near-commercial technologies). Of course, innovation does not stop there but may continue into full deployment and market diffusion as is clear from the dynamic theories of innovation briefly considered next.

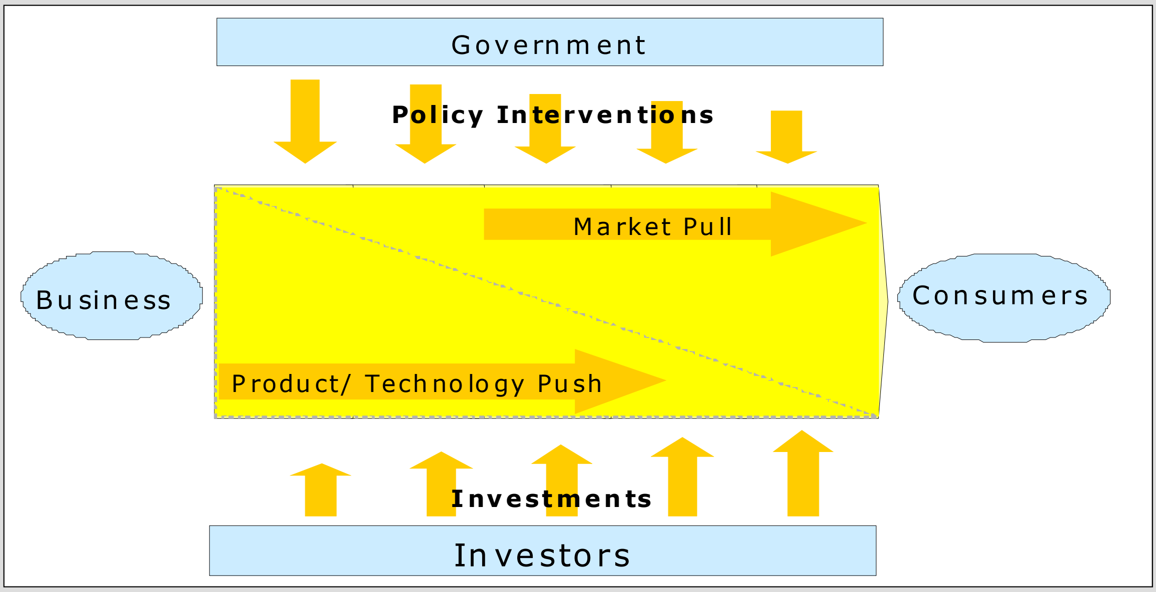
Stage	**Description of Activity**
TRL 1-3 Basic Research	Activity driven by a desire to broaden scientific and technical knowledge, and is not explicitly linked to industrial or commercial objectives. It typically includes investigating the underlying foundations of phenomena and observable facts, and typically takes place almost entirely in the academic community.
TRL 3-5 Development	Research with a more direct commercial application, driven both by scientific enquiry (with a degree of public good in the outcomes) and commercial opportunity (with research areas driven by expertise in spotting market opportunity), and is seen as an opportunity to build and develop links between industry and academia increasing the likely success and pull through of ideas from the academic community.
TRL 6-7 Demonstration	Large-scale pre-commercial demonstration of technologies, designed to test and improve longer term operational reliability, develop and improve full scale designs, establish and reduce operating costs and take the technology to a stage where the technology becomes a potential commercial investment. Work is undertaken by the private sector, typically with some academic involvement.
TRL 8-9 Early deployment	Technologies have been shown to work on a large scale, but are not yet competitive in the market, require a policy and market framework that supports their deployment. Development is undertaken by companies in the private sector.

Table 2.1: Description of Technology Readiness Levels (TRL)
Source: Frontier Economics (2009), Table 3, p.10; based on ETF (2008), p.13.

2.1 Technology Push and Market Pull

One of the commonest descriptions of the way technologies are developed and diffused in society is in terms of 'technology-push/market-pull', as illustrated in Figure 2.1. This suggests that technologies are developed through basic and applied research and development (R&D), to demonstration and commercialisation and thereby diffused into society.

The first, pre-market phases of the process are described as 'technology push', because the principal drivers are the business and policy decisions, including government investment in R&D and the activities and interests of scientists and engineers, that cause the technology to be developed. The commercialisation and diffusion processes are much more driven by consumer demand-pull in the markets which have been targeted or into which the technologies will by then have penetrated to some extent. Clearly, as shown, both sets of drivers are present to some extent in all phases: even at the earliest phases of technology R&D potential market demand is a major interest, and even during diffusion research-driven technological change may occur. For the process to take place successfully, continuous learning from and feedback between these processes are required.



- The innovation process involves the development and deployment of new technologies, products and services by business in order to meet the needs of consumers. To achieve this, funding is required from a variety of investors, such as insurance companies, banks, private equity houses and angel investors.
- In the early stages of the market, take-up is largely driven by the product/technology push. As consumer awareness builds, the rate of deployment is accelerated as consumer demand grows.
- Government can make various policy interventions at various stages of the innovation chain to overcome barriers to the development of various technologies, products and services.

Figure 2.1. Roles of Innovation Chain Actors (Source: Foxon 2003, p.18, after Carbon Trust 2002)

Each stage of the process may require, or be subject to, private investments or policy interventions (which may include government investments). At the R&D stages, at least for technologies which are thought to be of major potential public benefit, policy interventions are likely to be relatively important (shown by the length of the arrows). From demonstration onwards private investments are likely to be relatively important. However, especially for technologies of potential public benefit but uncertain market demand (of which hydrogen technologies may be a good example) it is likely that public support and policy interventions will be necessary both to help the technology from the demonstration to commercialisation stages (a risky transition sometimes called the 'valley of death' (e.g. Wessner, 2005), because of the business casualties and the demise of potentially good ideas, technologies and innovations, which it often induces), and even right through to the diffusion stage.

The linear nature of the technology-push/market-pull model has been criticised by Kemp & Foxon (2007), who recommend instead the more interactive 'chain-linked' model developed by Kline & Rosenberg (1986), illustrated in Figure 2.2, in which research and knowledge creation takes places throughout the innovation and product development, design and marketing stages. Such a model is certainly consistent with the recent investigation of the inter-relationship between propositional (basic scientific) and prescriptive (technical know-how) knowledge of Mokyr (2002).

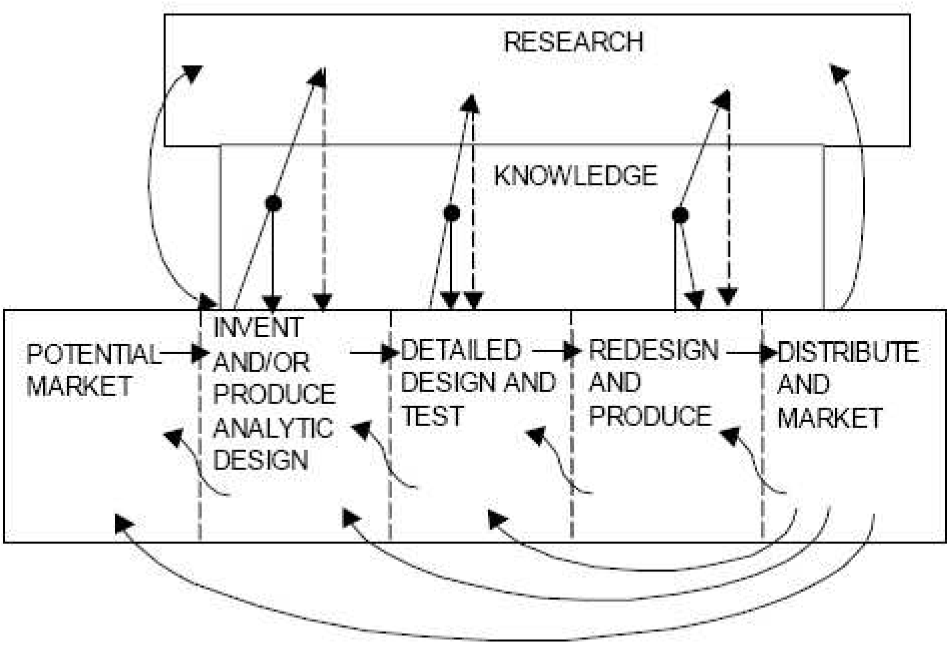


Figure 2.2: A chain-linked model of the innovation process
Source: Kline & Rosenberg 1986

While technology-push and market-pull may be important aspects of technological change, they contain no element of the social context in which such change is taking place, and therefore are clearly insufficient concepts by themselves to explain the much more widespread changes that are implied by the term ‘technological transition’. This requires an approach which takes a much wider view of the social and economic system in which technologies are embedded and which provide the context in which they thrive and decline.

2.2 Co-evolution of social sub-systems

Fundamental changes in technology are now understood to be processes that are rooted at the deepest level in the social contexts in which they occur. For example, the evolutionary approach to technological development adopted by Freeman & Louça (2001, p.121) proposes that such development requires the co-evolution of five ‘semi-autonomous’ social subsystems: science, technology, economics, politics, culture. They are semi-autonomous because, although the five variables are linked and interact, they also have autonomous elements. Fundamental technological changes (such as, for example, the development of a low-carbon energy system) are possible when, and only when, the co-evolutionary direction of change of all five variables is basically supportive of such change.

Freeman and Louça themselves do little to explore the implications of their insight into the necessary co-evolution of the five sub-systems, but it seems useful to useful here to distinguish between, and elaborate somewhat, the physical and socio-economic sub-systems, as follows:

- **The Physical Dimension**, which deals with the physical issues involved in the production/storage/distribution/end use of hydrogen, and has the following components:
  - *Science* the physically possible
  - *Technology* physical realisation of the physically possible
  - *Infrastructure* physical (including technical) support and diffusion of the physical realisation
- **The Socio-Economic Dimension**, which deals with the interests and drivers that push technical change along: *entrepreneurs* (and profits), *consumers* (and preferences), and *public policy* pressures, and has the following components:
  - *Economics* issues of allocation, distribution, competition
  - *Institutions* legal, financial, regulatory, planning frameworks
  - *Political Drivers* social perceptions driving political priority (security of supply, environmental issues) and the planning system, and the policy instruments through which these perceptions are implemented
  - *Culture* social perceptions driving social acceptability and consumer demand

These categories help to clarify that a major technological transition will only begin in earnest when some combination of entrepreneurs, consumers and public policy pressures generates both the investment in science, technology and infrastructure that physically permits environmental technologies to be widely deployed, and the economic, institutional and cultural conditions that make their widespread diffusion economically competitive and institutionally and socially acceptable.

2.3 Socio-technical landscapes and regimes, and technological niches

Another (though not contradictory) approach to technological transitions is taken by Geels (2002a,b), who adopts a three-tier "multi-level perspective", the three levels of which are:

- The socio-technical landscape, material infrastructure and "widely shared cultural beliefs, symbols and values that are hard to deviate from" (Geels 2002a, p.102);
- The socio-technical regime, the institutional and mental structures ("knowledge base, engineering practices, corporate governance structures, manufacturing processes and product characteristics", Geels 2002a, p.98) that provide the framework for any pervasive technology; and
- The technological niche, spaces insulated from the competitive challenge from mainstream technologies, in which innovations can survive and, perhaps, develop.

Geels' concept of sociotechnological regime is an extension of the 'technical regimes' discussed by Rip and Kemp (1998) and Nelson and Winter (1982). According to Geels (2002b, p.1260), socio-technical regimes include not only the organisational and cognitive rules and routines adopted and followed by engineers and firms, but also the routines influencing the behaviour of "users, policy makers, social groups, suppliers, scientists and bankers etc.". The stability and persistence of a regime, and the widespread recognition of its function and purpose, derives from the fact that there is coherence between the incentives, rules and routines of these different actors: "The activities of these different groups are aligned and coordinated." (Geels 2002b, p.1259). Thus the socio-economic actors in the same regime share an overall common aim – the fulfilment of the regime function. Each actor in the regime has an incentive to co-operate, as they would be worse off if they took an action putting the existence of the regime at risk. Innovation under such circumstances, when it occurs, tends to be incremental and to result in improvements to (and reinforcement of) the existing regime, rather than a transition to a new regime. Edgerton (2006) confirms the importance of incremental innovation to historical technological change in the UK, and it seems likely that the wide range of technologies used in 'eco-industries' will be as much if not more likely to be introduced incrementally as through more radical technological disruption.

It may not always be straightforward to demarcate clearly the boundaries between different socio-technical regimes, while some elements of one regime might also belong to another. Hughes (1987, p.53) considered that a defining characteristic of technological systems is that they solve problems or fulfil goals, using whatever means are available and appropriate, where the problems have to do mostly with reordering the physical world in ways considered useful or desirable, at least by those designing or employing a technological system. More simply, Rip and Kemp (1998) define regimes as "configurations that work", a definition which Geels (2002a) makes clear refers to fulfilment by a regime, in an economically and socially acceptable way, of a *function* that is considered useful or desirable by some actor in the regime. There is consideration of how eco-innovation may be considered in terms of enhanced environmental and economic functionality in Section 3.

Identifying the main attribute of a regime as related to its functionality makes it easier to identify its core, if not precisely to delineate its boundaries: substantially different functions will be associated with different regimes (however, it is also clear that the functions defining a regime can evolve over time). Going beyond function, Geels (2002b, p.1262) identifies the seven key dimensions of a socio-technical regime as technology, user practices and application domains (markets), symbolic meaning of technology, infrastructure, industry structure, policy and techno-scientific knowledge. Although these dimensions change through their own internally generated impulses, they are also linked and co-evolve in the same way as Freeman & Louça's social sub-systems described above. The stability of the regime comes from the coherence of and linkages between the dimensions. Regime change arises when this coherence or the linkages weaken.

Regime stability also derives from the process of technological 'lock-in', which Arthur (1988, p.591) identified as deriving from five factors, which, once they are operational in favour of a particular technology, tend to give it a competitive advantage against which it is increasingly difficult for competing technologies to counter. The five factors are:

- *Learning by using*, which accelerates technological improvement
- *Network externalities* – the more widely a technology is used, the more applications are developed for it and the more useful it becomes
- *Economies of scale*, which reduce the unit price

- *Increasing informational returns*, linked to learning by using, whereby the increased numbers of users, knowing more about the technology, makes it easier for others to learn about the technology
- *Development of complementary technologies,* which both reinforce the position of the technology and make it more useful.

The concept of technological lock-in is often used to describe the persistence of sub-optimal technologies (the QWERTY keyboard is the most often quoted example, see David 1985), but these processes are actually characteristic of all successful technologies, sub-optimal or not. If there is to be a transition to the hydrogen economy, hydrogen technologies will need to be subject in large measure to all these processes.

There is also the issue of how broad a regime needs to be in order to qualify as such. Regimes may be seen to be 'nested' within each other. Berkhout et al. (2003, p. 9) ask whether the fundamental shift in pesticides brought about by the banning of DDT amounted to an agricultural regime change, or whether it left intact the wider regime of a chemical-intensive agriculture.

At a higher level than the regime, Geels (2002b)'s socio-technical landscape provides an external "structure or context for interactions among actors" (Geels 2002b, p.1260) in a regime. This landscape contains a set of "heterogeneous factors, such as oil prices, economic growth, wars, political coalitions, cultural and normative values and environmental problems. The landscape is an external structure or context for interactions of actors. While regimes refer to rules that enable and constrain activities within communities, the 'ST-landscape' refers to wider technology-*external* factors" (Geels, 2002b, p.1260, emphasis in original). A similar definition describes landscapes as composed of "background variables such as material infrastructure, political culture and coalitions, social values, worldviews and paradigms, the macro economy, demography and the natural environment, which channel transition processes and change themselves slowly in an autonomous way" (Kemp & Rotmans, 2001, cited in Berkhout et al. 2003, p.6).

The internal/external distinction between regimes and landscapes seems more useful than another distinction used by both Kemp & Rotmans and Geels, relating to speed of change: "landscapes do change, but more slowly than regimes" (Geels, 2002b, p. 1260). This is by no means obvious. The external factors which belong to landscapes can in fact change very quickly. Oil prices, which historically have been very volatile, are one example. So are the geopolitical circumstances that can affect (perceptions of) energy security. So are the political perceptions of the priority of an issue like climate change. Changes in any or all three of these examples of landscape factors might be important in stimulating a technological transition towards far great use of environmental technologies. Through these examples it can be seen that changes in the socio-technical landscape can be the means whereby the stability and internal coherence of a socio-technical regime can be undermined.

Another distinction between the factors belonging to regimes or landscapes might be the extent to which they can be influenced by the socio-economic actors involved in the regime. Clearly, this varies among different actors. For example, the oil price can hardly be affected by individuals, but governments can have more effect. A rule of thumb for distinguishing between regime or landscape factors might be: if socio-economic actors can influence the direction, the timing or the rapidity of the change in a factor more than the extent to which they are influenced by it, this factor is likely to be part of the regime; in the opposite case that element will belong to the landscape. But the degree of influence is likely to vary for different actors and in different situations, so that it is not a hard and fast distinction. Such considerations suggest that, rather than being clearly differentiated, landscapes and regimes at different levels merge into each other by displaying some common, but other clearly differentiated, elements and characteristics that are all subject to change.

In the final analysis, because of the wide-ranging nature of the concepts of socio-technical landscapes and regimes, it probably needs to be accepted that no taxonomy is likely to distinguish unambiguously between different regimes, and between the elements belonging to the regime and those belonging to the landscape. More distinct is the third element of Geels' multi-level perspective, the concept of the niche.

The niche is in fact a longstanding theme in relation to the diffusion of innovations and technological change (see for example, Foxon 2003, Kemp et al., 1998, Wallace 1995), focusing on such issues as the importance of the size of the niche market, the technical and financial capabilities of suppliers, and stable investment conditions as key for successful diffusion. In the context of hydrogen fuel cells, Adamson (2005) defines niche markets as "small protected market[s] that a new disruptive innovation enters before it reaches the mass market" (Adamson 2005, p.343), and Geels (2002a,b) seems to share that perception, seeing a fundamental property of niches that they "act as 'incubation rooms' for radical novelties", and offer some protection from normal market selection in the regime (Geels, 2002b, p. 1261). However, it is not clear why only disruptive innovations should inhabit niche markets, as seems to be implied by Adamson (2005). It seems quite possible for non-disruptive innovations also to be found in niche markets although they may not have the potential to break into the mass market and may exist in their niche for a considerable period of time. Nor is it clear why technologies in niches need necessarily to be protected from competition with technologies in the mass market (they may contain valued functional characteristics that distinguish them from such technologies). In fact niche markets may more simply be viewed as small, focused and targetable portions of a larger market, comprising a group of actors whose needs for products or services to perform particular functions are not being addressed by mainstream providers. Niche markets may function as incubators for new technologies, and that this can occur in the absence of protection from market competition in the regime, when the new technologies in question have functionalities (such as improved environmental performance) that are desired by a (small) group of consumers, such as, for example, 'green' consumers who seek out environmentally superior goods and services. Clearly an ETR (a landscape change) can narrow the price difference between such niche markets and comparable mainstream markets with goods and services that are inferior environmentally, thereby making it more likely that more consumers will purchase the environmentally superior goods and services, and allowing the niche to expand until, eventually, it may become the dominant technological regime. In this way the three levels of Geels' multi-level perspective can be brought together to show how jointly they can explain technological transitions.

4. TECHNOLOGIES AND SCENARIOS FOR LOW-CARBON INNOVATION IN THE ENERGY SYSTEM

In a widely cited approach, Socolow et al. (2004) suggest that, even to stabilise global carbon emissions at 2004 levels, seven low-carbon technologies would need to be widely implemented such that each one was able, after half a century, to ensure that global emissions were 1 GtC (gigatonne of carbon) lower than they would otherwise be, i.e. each technology would take out a 'wedge' of 1 GtC by 2054. They further suggest that 15 energy-related technologies, in five categories, have this potential:

- Energy conservation in power generation, transportation, and industry and buildings
- Renewable energy, for electricity, heat and motor fuels
- Natural carbon sinks, namely forests (both plantations and the reduced loss of existing forests) and soils
- Nuclear energy
- Fossil-fuel management, both in terms of moving away from coal and capturing and storing carbon.

These technology 'wedges' vary greatly in terms of their cost per tonne of carbon saved, their commercial availability and even as to whether they have been proven at the kind of scale envisaged. Their full development and implementation will undoubtedly require determined stimulation and support through public policy, which is briefly discussed later. First, however, the results of a simulation are reported, in which an energy system model was used to project how the UK energy system might develop in a low-carbon direction, which technologies among some of those mentioned above might be employed and what the associated costs would be.

Low-Carbon Scenarios for the UK

A number of trajectories of possible low-carbon reductions for the UK energy system have been projected, using a newly developed and updated UK MARKAL elastic demand (MED) model. Such modelling is designed to develop insights on possible future energy system evolution and the resultant technology pathways, sectoral trade-offs and economic implications.

MARKAL is a widely applied technology-rich, multi-time period optimisation model. For the UKERC Energy 2050 project a major development was the implementation of an elastic demand version (MED) to account for the response of energy service demands to prices. The model's new objective function of the sum of consumer and producer surplus is considered a valid metric of social welfare, and hence gives insights into a key behavioural implication of energy system changes. Additional MED model development included updated fossil resource costs; expanded categorisation of UK carbon capture and storage (CCS) and wind resources; expanded biomass chains to all end-use sectors; new hydrogen (H_2) infrastructures, improved treatment of electricity intermittency; non-price representation of residential energy service demands and technology assumptions; a range of updated electricity technology assumptions; buildings technology updates (including micro-CHP [combined heat and power] and heat pumps); transport technology updates (including plug-in hybrid electric vehicles); updated energy service demand assumptions; and incorporation of all UK policy measures through 2007 (including the then-current carbon price in the EU Emissions Trading Scheme [EU-ETS] price).

The MED model was fully recalibrated to standard UK energy statistics. An important point to stress is that MARKAL is *not* a forecasting model and does *not* predict the future UK energy system over the next 50 years. Instead it offers a systematic tool to explore the trade-offs and tipping points between alternative energy system pathways, and the cost, energy supply and emissions implications of these alternative pathways.

A comprehensive description of the UK MARKAL model, its applications and core insights can be found in Strachan et al. (2008a), and the model documentation (Kannan et al., 2007). Peer reviewed papers focused on specific variants and/or applications of the UK MARKAL model include Strachan and Kannan (2008), Strachan et al. (2009a), Kannan et al. (2008), Strachan et al. (2008b) and Strachan et al. (2009b). The modelling described briefly here is discussed in more detail in Anandarajah et al. 2008.

The set of scenarios (CFH, CLC, CAM, CSAM) reported here focus on carbon ambition levels of CO_2 reductions (in 2050) ranging from 40% to 90% reductions. These runs also have intermediate (2020) targets of 15% to 32% reductions by 2020 (from the 1990 base year). These scenarios investigate increasingly stringent targets and the ordering of technologies, behavioural change and policy measures to meet these targets. The 80% reduction target (in CAM) is in line with the now statutory target in the UK Climate Change Act, which became law in 2008. Together with a base reference case, the four decarbonisation scenarios are detailed below in Table 3.1.

Scenario	Scenario name	Annual targets (reduction)	Cumulative targets	Cum. emissions $GTCO_2$ (2000-2050)
B	Base reference	-	-	30.03
CFH	Faint-heart	15% by 2020 40% by 2050	-	25.67
CLC	Low carbon	26% by 2020 60% by 2050	-	22.46
CAM	Ambition	26% by 2020 80% by 2050	-	20.39
CSAM	Super Ambition	32% by 2020 90% by 2050	-	17.98

Table 3.1: Carbon reduction scenarios

The runs employ a market discount rate of 10% to trade-off action in different time periods as well as annualise technology capital costs. This 10% market discount rate is higher than a risk-free portfolio investment return (which could be around 5%) and accounts for the higher return that investors require to account for risk. In addition the model uses technology specific 'hurdle' rates on future transport technology and on building conservation and efficiency options. These hurdle rates apply only to, and effectively increase, the capital costs of these efficiency technologies, in order to simulate the barriers to investment in them. Set at 15%, 20% and 25% these hurdle rates represent information unavailability, non price determinants for purchases and market imperfections (e.g., principal agent issues between landlords and tenants).

The intuition behind these different discount and hurdle rates is as follows. The market discount rate describes situations in which markets work perfectly and it is considered appropriate that market criteria should govern all (including social and government) decision-making. Hurdle (higher than market) rates are introduced to take account of market imperfections which impede investments. There now follow results from the scenarios for the different variables of interest.

CO_2 Emissions

If no new policies/measures are enacted, energy related CO_2 emissions (in the Base Reference Scenario, B) in 2050 would be 584 $MtCO_2$, which is 6% higher than the 2000 emission level and only 1% lower than the 1990 emission level. Existing policies and technologies would bring down the emissions in 2020 to about 500 $MtCO_2$ achieving over 15% reductions, which falls well short of the (then) minimum government target of a 26% reduction. From 2020-2050, economic and energy service demand growth overwhelms near term efficiency and fuel switching measures (which are partially driven by the effects of the EU-ETS price, and the electricity and transport renewables obligations), and CO_2 emissions rise. Figure 3.1 provides annual CO_2 emission levels under different scenarios over the projection period. For nearer-term emissions reductions (2020), the CO_2 emissions constraint in 2020 is imposed in CLC and CAM (26%) and CEA and CSAM (32%).

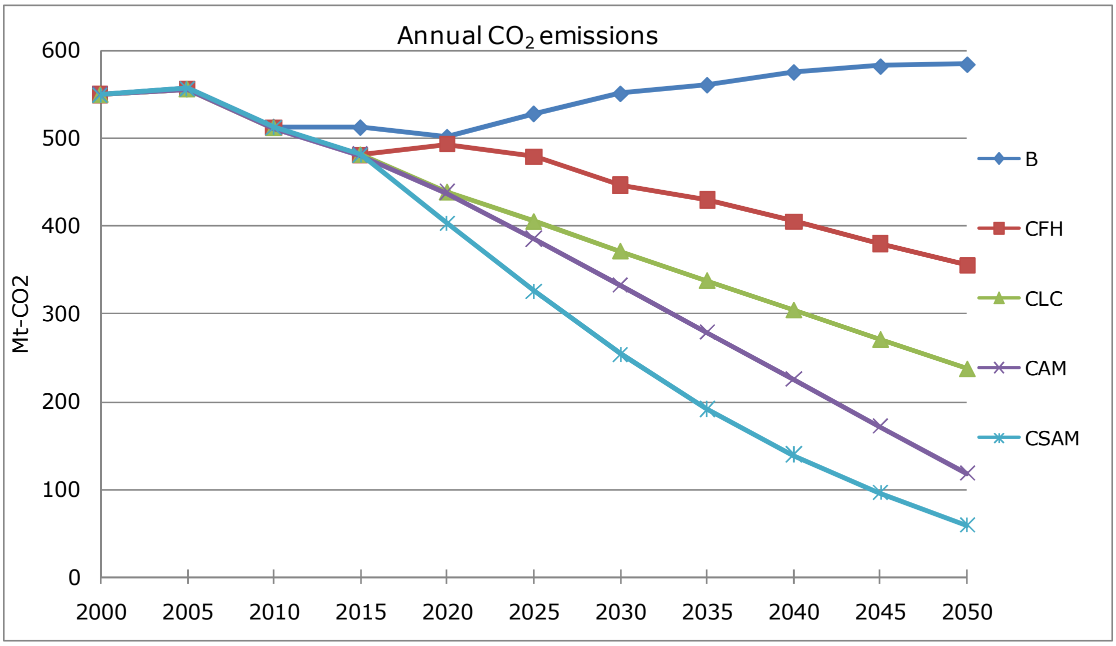


Figure 3.1: CO_2 emissions under scenarios with different annual carbon constraints

Sectoral CO_2 emissions

Figure 3.2 presents the sectoral CO_2 emissions in B, CFH, CLC, CAM and CSAM for the selected years 2035 and 2050. Decarbonisation is foremost in the power sector until the middle or end of the projection period. Then major efforts switch to the residential and/or transport sector. Service sector and upstream emissions are also heavily decarbonised in the CAM and CSAM cases in 2050 as the residual emissions budget shrinks. Residential and transport sectors work harder to meet relatively higher early mitigation target in CSAM, reducing their emissions respectively by 67% and 47% in 2035 as compared to B.

To meet the 80% target in CAM, the power sector CO_2 emission is reduced by 93% compared to B in 2050. The respective figures for the residential, transport, services and industrial sector are 92%, 78%, 47% and 26% respectively. Since the industrial sector is only moderately decarbonised, in 2050 it is the prime contributor to the remaining CO_2 emissions in CAM and CSAM, followed by transport sector.

Electricity decarbonisation via CCS can provide the bulk of a 40% reduction in CO_2 by 2050 (CFH). To get deeper cuts in emissions requires three things: a) deeper de-carbonisation of the electricity sector with progressively larger deployments of low-carbon sources; b) increased energy efficiency and demand reductions particularly in the industrial and residential sectors; c) changing transport technologies to zero carbon fuel and more efficient vintages. For example, by 2050, to meet the 80% target in CAM, the power sector emissions are reduced by 93% compared to the base case. The reduction figures for the residential, transport, services and industrial sectors are 92%, 78%, 47% and 26% respectively. Hence remaining CO_2 emissions are concentrated in selected industrial sectors, and in transport modes (especially aviation). End-use sectors have their lowest CO_2 emissions in CSAM, which has the highest mitigation target of 90% in 2050.

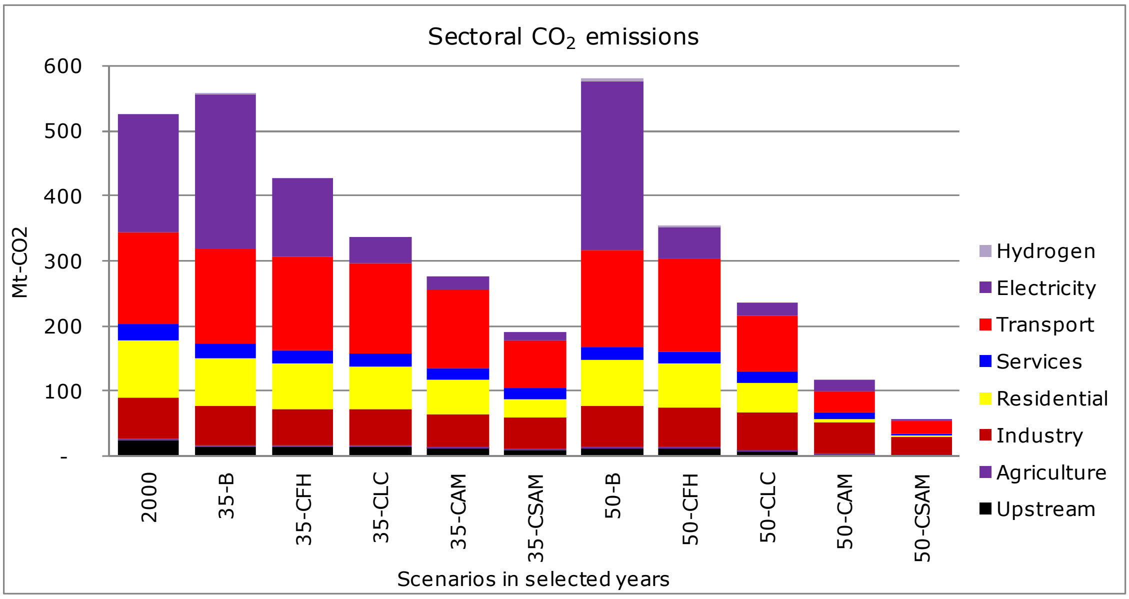


Figure 3.2: Sectoral CO_2 emissions in years 2000, 2035, 2050: Carbon ambition scenarios

Power Sector Capacity

Figure 3.3 shows that coal, nuclear and a small amount of gas-based power plants are selected for the base load generation in the Base reference case, B. Existing coal plants dominate in the early part of the projection period, but are gradually replaced by pulverised fluidization technology, their capacity gradually increasing from 17GW in 2020 to 50 GW in 2050. The share of nuclear plants in base load capacity decreases from 33% in 2010 to 2% in 2035 due to the retirement of the plants. A growing capacity of gas turbine combine cycle (GTCC) plant is also selected to serve as base load installed capacity from about 1 GW in 2010 to 13GW in 2050. Wind, particularly on-shore wind, plays a major role for non-base load, with over 12 GW during 2015-2050. In the middle part of the period, a large quantity of sewage and landfill gas IC engines are also selected, their capacity increasing from 2.5 GW in 2015 to 13 GW in 2025. As the share of base load plants in total installed capacity is relatively high at the end of the projection period, the capacity of the sewage gas plants declines to 1 GW in 2050. Further, 3 GW and 5 GW of tidal stream are selected in 2045 and 2050 respectively.

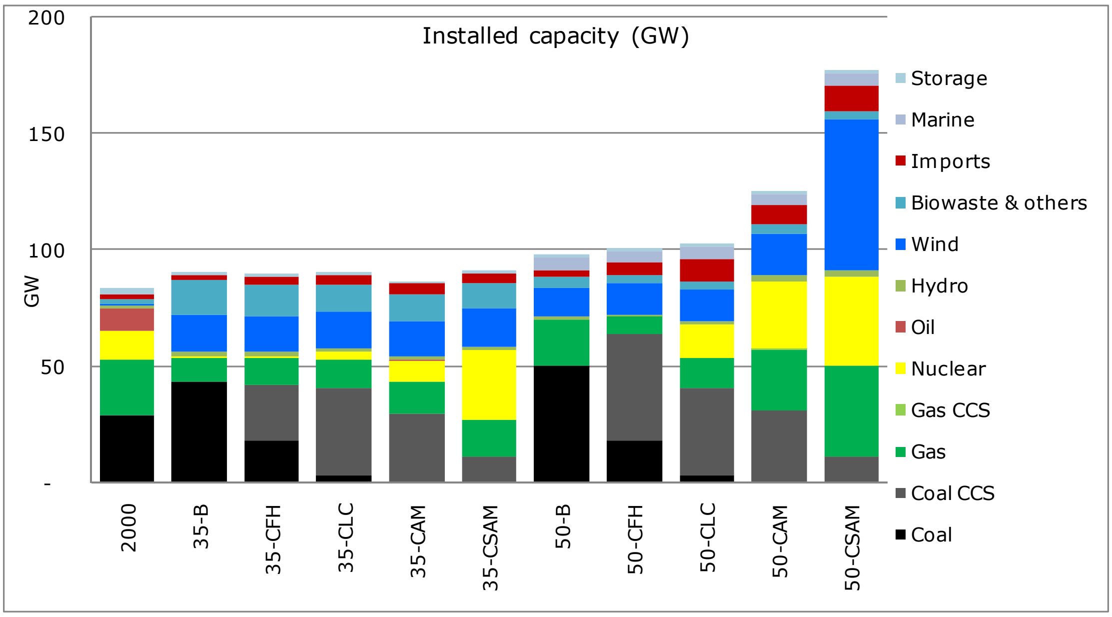


Figure 3.3: Installed capacity under different scenarios

When CO_2 emissions are increasingly constrained, the UK MARKAL model strongly decarbonises the electricity sector, and there is a huge change in the capacity mix in the power sector. The decarbonisation of end-use sectors by means of shifting to electricity as well as selection of non-peak contributing plants, which needs reserve capacity, increases the installed capacity level in the mitigation scenarios particularly during the latter part of the projection period.

Though there are several available broadly competitive options including renewables, nuclear power and carbon capture and storage (CCS) associated with coal and gas-based fossil fuel power stations, decarbonisation of the power sector begins with the deployment of CCS for coal plants in 2020 in all mitigation scenarios, with non-CCS coal in 2035 only remaining in any quantity in CFH, with its relatively low mitigation target. Coal-CCS is the main technology to meet the mitigation target in CFH and CLC in the later period. Coal-CCS decreases with the increased CO_2 reduction target level in CAM and CSAM, as the carbon capture rate is only 90% (i.e., there are 10% residual emissions). Nuclear is selected at the cost of CCS to meet the carbon target in CAM. A large amount of wind is selected with the 90% target in 2050 of CSAM, together with a large capacity of back-up gas plants. The technology learning rate, which reduces the capital costs of technologies over the period, also affects the results, with marine for example becoming cheaper and being selected in 2045 because of its relatively high learning rate.

It should be stressed that, although decarbonisation begins in all mitigation scenarios with the deployment of carbon capture and storage (CCS) for coal plants in 2020-2025, there is considerable uncertainty over the dominant player in any optimal technology portfolio of CCS vs. nuclear vs. wind, due to the close marginal costs and future uncertainties in these technology classes. Specifically, when examining the investment marginal costs when CCS technologies are the least cost, across the scenarios from 2030-2050 further tranches of offshore wind would be competitive with a cost improvement of between £56-260/kWe installed - this represents only 5-25% of capital costs. Nuclear's marginal investment costs are even closer to CCS, at between £2-218/kWe installed, depending on the scenario and time period.

Power Sector Generation

Electricity generation mixes under B, CFH, CLC, CAM and CSAM are shown in Figure 3.4 for selected years 2035 and 2050. In the Base B, electricity generation increases by 24% during 2000-2050 to meet continuously increasing electricity demand in the end-use sectors. In the absence of significant CO_2 pricing, high carbon content coal becomes the dominant fuel for electricity generation gradually replacing gas and nuclear over the years, generating more than 80% of the total electricity supplied in 2050.

Total electricity generation would increase or decrease in the mitigation scenarios as compared to that in the Base reference case depending on the electricity demand. In 2035, electricity generation decreases in line with the successive targets CFH, CLC and CAM (not in CSAM), because of efficiency improvement and demand reduction of end-use sectors. Conversely, as decarbonisation efforts tighten through 2050 (and throughout the period for CSAM), electricity generation increases in line with the successive targets including CSAM, with end-use sectors shifting to electricity. Hence there is a trade off, with the decarbonisation of end-use sectors tending to increase demand for electricity, while both efficiency improvements and demand reductions tend to reduce it.

The electricity sector has highly important interactions with transport (plug-in vehicles) and buildings (boilers and heat pumps), as these end-use sectors contribute significantly to later period decarbonisation. As a result, electricity demand rises in all scenarios, and is roughly 50% higher than the base level in 2050 in most of the 80% reduction scenarios.

The shift to electricity use in the residential sector (from gas), combines with technology switching from boilers to heat pumps for space heating and hot water heating. The service sector is similarly decarbonised by shifting to electricity (along with biomass penetration in the most stringent scenarios). Natural gas, although increasing in efficiency, is still used in the residential and service sectors for space heating and is a contributor to remaining emissions.

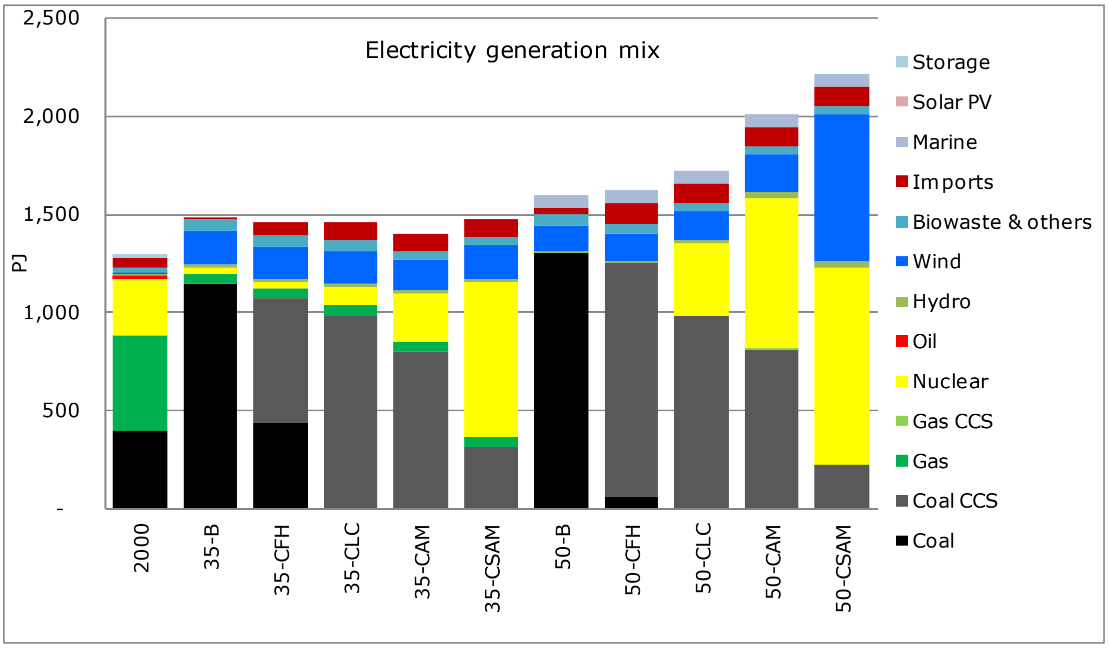


Figure 3.4: Electricity generation mix under different scenarios

As carbon reduction requirements cause emissions to fall to very low levels in the power sector (almost complete decarbonisation in 2050 in CSAM) the role of coal CCS is assisted and eventually supplanted by nuclear and wind as available CCS capacity is used for hydrogen production and as residual CCS emissions are squeezed out. A large amount of electricity (more than one third) is generated from wind (with capacity balancing) in CSAM in 2050.

Transport Sector

Cars are the biggest energy consumers in the UK transport sector, accounting for over half of the transport sector energy demand in B (Figure 3.5). This is mainly due to the high demand for transport services in terms of passenger-km in the base years as well as the expected high growth rate during the period. In the Base reference case, petrol and diesel IC engines cars are selected to meet the demand for cars while in 2-wheelers only petrol engines are selected. In the bus mode, there are complete transitions from diesel to diesel hybrid during 2010-2015 and then from hybrid to battery operated electric buses during 2040-2045 in B itself. Hybrid (diesel) vehicles replaces diesel based HGV and HGV during 2010-2015 and thereafter there is no technological change or fuel switch for the goods vehicles in the Base reference case.

In the carbon ambition mitigation scenarios (CFH, CLC, CAM and CSAM), the transport sector is decarbonised via a range of technology options by mode, but principally first by electricity (hybrid plug-in), and later by bio-fuel vehicles in more stringent scenarios (CAM, CSAM) (Figure 3.5). As the transport sector is not heavily decarbonised in 2035, there are only small reductions in the energy demand between the CO_2 mitigation scenarios. In 2035 under the largest change in CSAM, where the transport sector has to work harder, decarbonisation is mainly by shifting to Car-ethanol (E85) (55%) and, to a smaller extent, to petrol plug-in cars (11%). In 2050, there is a trade-off between options to reduce energy service demands, efficiency to further reduce final energy, and use of zero-carbon transport fuels. A significant difference in energy demand can be observed in the higher target scenarios (i.e. not

CFH) as the transport sector is decarbonised in the latter part of the period. For example bio-fuels in stringent reduction scenarios do not reduce energy demand as their efficiency is similar to petrol and diesel vehicles. Therefore, although transport sector CO_2 emissions are the lowest in CSAM, its energy demand is higher than in CAM, because of the larger consumption of bio-diesel and ethanol in CSAM and greater penetration of plug-in cars in CAM and CLC. Different modes adopt different technology solutions depending on the characteristics of the model. Cars utilize plug-in vehicles and then ethanol (E85). Buses switch to battery options. Goods vehicles (HGV and LGV) switch to bio-diesel then hydrogen (only for HGV).

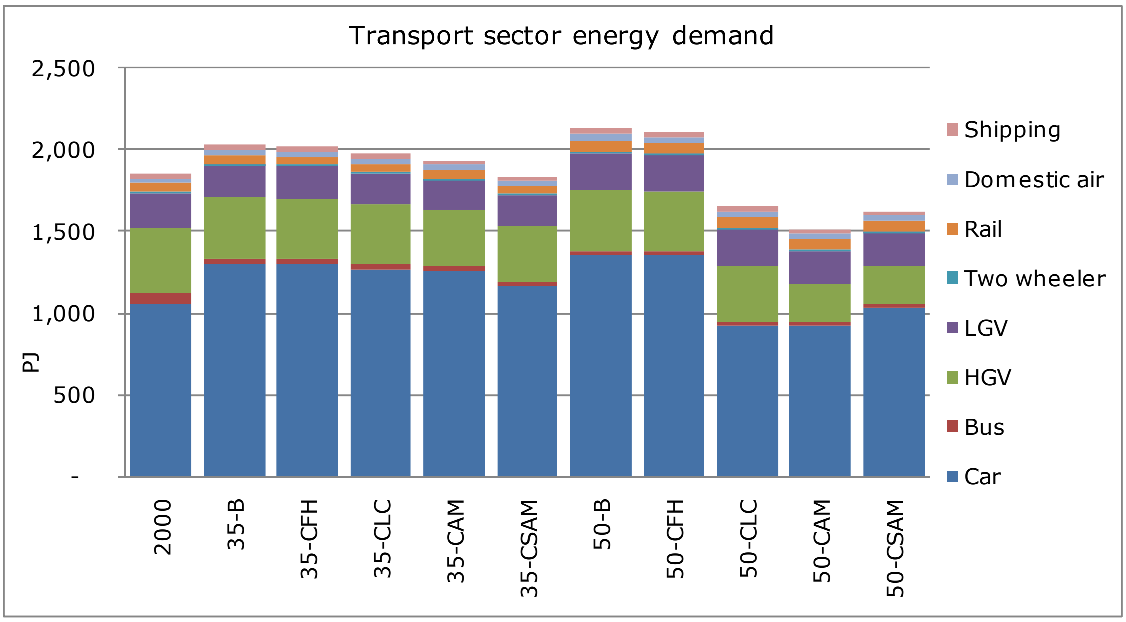


Figure 3.5: Transport sector energy demand by modes under different scenarios

Final Energy Demand

Figure 3.6 shows the final energy demand by fuel types for selected years in B, CFH, CLC, CAM and CSAM. Gas is the dominant fuel in the base year as well as in 2035 accounting more than one third of the final energy demand in all scenarios. Overall, although the share of gas is decreasing over time in the low carbon scenarios, still gas and electricity dominate the final energy demand in all scenarios except CSAM in 2050. The share of electricity in total final energy demand is only 19% in 2000, but its share increases continuously throughout the period, reaching 23% in 2050. Petrol and diesel together meet about one third of the final energy demand with diesel having a slightly higher share in the early and middle period. Bio-energy (bio-diesel and ethanol) plays a considerable role in CSAM in 2050. The transport sector consumes large amount of bio-energy (ethanol and bio-diesel) leading to greater final energy demand in CSAM as compared to CAM as the efficiency of bio-diesel based vehicles is relatively low compared to the hybrid plug-in vehicles. Further, large amount of biomass is used in the service sector for heating. Note that the remaining (high efficiency) gas will be a major contributor to residential and service sector CO_2 emissions, along-with transport (including aviation) and industrial liquid fuels.

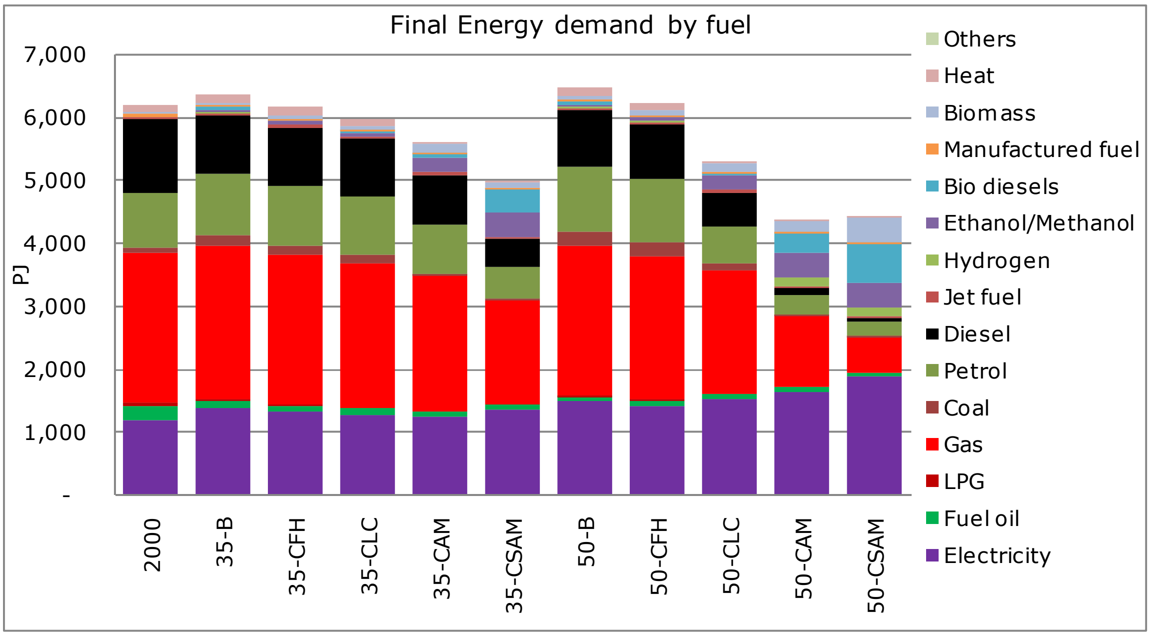


Figure 3.6: Final energy demand by fuel under different scenarios

It may be noted that these least-cost optimal model scenarios do not produce decarbonisation scenarios that are compatible with the EU's draft renewables directive of at least 15% of UK final energy from renewables by 2020. Major contributions of bio-fuels in transport and offshore wind in electricity production only occur in later periods following tightening CO_2 targets and advanced technology learning.

The Role of Demand Reduction

In addition to efficiency and fuel switching (and technology shifting), the price elasticity, by reducing energy service demands, also plays a major role in reducing CO_2 emissions by reducing energy service demands. In fact, demand reduction is one of the model's preferred options to reduce CO_2 emissions, notwithstanding the societal loss in utility due to the demand reduction. The MARKAL MED version's objective function maximises the combined producer and consumer surplus, and includes demand reductions when finding the optimal solution.

The level of demand reduction is influenced by the demand function that is constructed based on the price elasticity and reference prices of the Base case. The demand reduction level then depends on both the price elasticity of demand and the prices of alternative technologies and fuels available to meet the particular energy service demand. For a particular energy service demand, if the alternatives are available with a relatively high incremental cost, then the demand reduction level would be high (or vice versa). For example, the price elasticity of demand is very low for transport shipping (-0.17) and very high for transport HGV (-0.61). However, demand reduction is relatively higher for transport shipping than transport HGV as the transport shipping has no alternative technologies in the UK MARKAL model other than diesel, which is a high carbon content fuel, while the transport HGV has many alternative technologies such as diesel ICE, diesel hybrid, hydrogen ICE and hydrogen fuels. Similarly, car demand also has a relatively high price elasticity (-

0.45), but because of the availability of the alternative technology with relatively cheaper cost, the demand reduction level is low.

Not surprisingly, demand reduction levels are lowest in CFH for all sectors. The level of demand reduction increases with the successive mitigation targets in CFH, CLC, CAM and CSAM in 2035 and 2050. Demand reductions in the agriculture, industry, services and residential sectors are combinations of reduced individual energy service demands for the sub-sectors of the respective sectors. Relatively high elasticities and restricted technology options for residential demand (notably direct electricity and gas use) and industrial sectors (notably chemicals) results in substantial reductions in energy service demands in those sectors. Reaching 20-25% reductions in service demands implies both a significant behavioural change and an industrial reorientation process concerning energy usage.

Agriculture, industry, residential and international shipping have higher demand reductions than aviation, cars and HGV (heavy goods vehicles) transport sectors. This is driven both by the elasticities in these sectors but crucially by the existence of alternative (lower cost) technological substitution options. Significant energy service demand reductions (up to 25%) in some scenarios in key industrial and buildings sectors imply employment and social consequences that would need to be taken into account in the policies that brought them about.

Marginal carbon costs of mitigation

MARKAL is a least-cost optimisation model, and the model produces marginal emissions prices to meet the CO_2 constraints based on a range of input assumptions, including competitive markets, rational decision-making and perfect foresight. Note that emission trading could be a cheaper option (buying carbon credits), if the international carbon price is less than the UK MARKAL marginal cost of CO_2, but these runs focus only on national CO_2 reductions. The marginal prices shown in Figure 3.7 illustrate that marginal emission prices rise as the annual CO_2 constraint tightens across scenarios and through time. In 2035 marginal CO_2 prices rise from £13/tCO_2 in CFH to £133/tCO_2 in CSAM, and by 2050 this range is £20/tCO_2 to £300/tCO_2. This convexity illustrates the difficulty of achieving very deep CO_2 reductions.

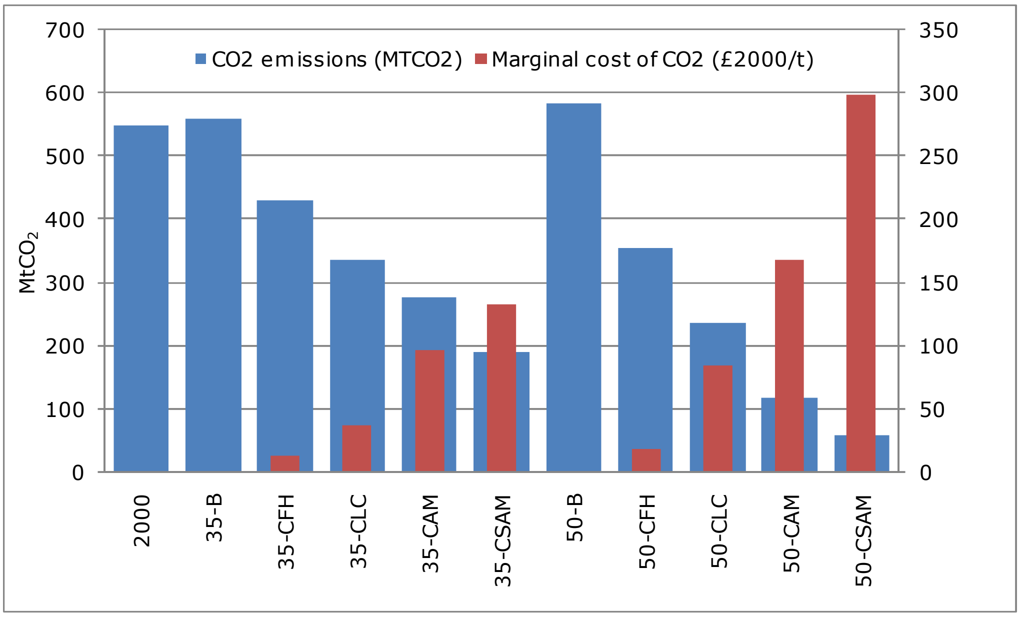


Figure 3.7: Carbon ambition runs: marginal price of CO_2 and CO_2 emissions

Welfare Costs

Welfare costs (sum of producer and consumer surplus) in 2050 range from £5 - £52 billion. In particular moving from a 60% to an 80% reduction scenario almost doubles welfare costs (from £20 - £39 billion). Note that welfare cost is a marked improvement on energy systems cost as an economic impact measure as it captures the lost utility from the forgone consumption of energy. However it cannot be compared to a GDP cost as wider investment, trade and government spending impacts are not accounted for. It is also difficult to attribute the welfare loss components to either producers or consumers as this depends on the shape of the supply and demand curves, and crucially on the ability of producers to pass through costs onto consumers.

Overall, the Carbon Ambition runs follow similar routes, with additional technologies and measures being required and targets become more stringent and costs rapidly increase. For dynamic path dependence in decarbonisation pathways, we focus next on the range of sensitivity runs with the same cumulative CO_2 emissions.

Policy Discussion

Any policy discussion of these insights must recognise that these pathways and energy-economic implications come from a model with rational behaviour, competitive markets and perfect foresight on future policy and technological developments. Even so the policy challenges in achieving 80% CO_2 reductions in the UK are very considerable. Furthermore, policy makers need to be cognisant of the range of inherent uncertainties in long term energy scenarios, and future UKERC Energy 2050 reports will investigate a broad range of alternative drivers and developments.

Rising carbon reduction targets (from 40-90% in CFH through to CSAM) gives a corresponding rising price of carbon and the model ranges in 2050 from £20-300/tCO_2. For comparison, the Climate Change Levy at current rates amounts to an implicit carbon tax of £8.6/tCO_2 for electricity and gas, and £37.6/tCO_2 for coal. Duty on road fuels is currently (i.e. in 2008) about 50p/l. If this is all considered as an implicit carbon tax (i.e. ignoring any other externality of road travel), this amounts to about £208/tCO_2. This means that in the optimal market of the MARKAL model, rates of fuel duty would need to be about doubled in real terms by 2050, while tax on other fuels would need to have been imposed at about the current fuel duty rate at the same date, in order for the targets to be met. While these tax increases seem large, they are actually a fairly modest annual tax increase if they were imposed as an annual escalator over forty years.

In addition to reduced energy service demands from the price effect, MARKAL delivers reduced final energy demand through the increased uptake of conservation and efficiency measures. The relatively high uptake of the measures across scenarios indicates their cost effectiveness compared to other measures. Such savings would require strong and effective policy measures. It may be that the Carbon Reduction Commitment, an emission trading scheme for large business and public sector organisations due to be implemented in 2009, will provide the necessary incentives for installing the conservation measures.

One example of the uptake of efficiency technologies in buildings is heat pumps, which play a major role in all the 80% and 90% carbon reduction scenarios. At present the level of installation, and of consumer awareness, of heat pumps is very low indeed, and their installation in buildings is by no means straightforward. To reach the levels of uptake projected in these scenarios, policies for awareness-raising and training for their installation need to begin soon.

In the transport sector the model runs give a detailed breakdown of the uptake of different vehicle technologies, including those with greater energy efficiency. Energy service demands (in billion vehicle km) in the transport sector in 2050 are only moderately reduced as the carbon targets become more stringent, but the energy demand required to meet those energy service demands falls by considerably more, (from 2130 PJ in the Base to 1511 PJ in CAM). This results from a more than doubling of the efficiency of fuel use combined with a range of electric, bio-fuel and hydrogen zero-carbon fuel networks depending on scenario and transport mode. The development of these new vehicle types, and of more efficient existing vehicle types, will be partly incentivised by the carbon price, but is also likely to require an intensification of energy efficiency policies, such as the EU requirements to improve vehicle efficiency, and demonstration and technology support policies to facilitate the penetration of the new vehicle types and networks.

These model runs reveal the single most important policy priority to be to incentivise the effective decarbonisation of the electricity system, because low-carbon electricity can then assist with the decarbonisation of other sectors, especially the transport and household sectors. In all the scenarios, major low-carbon electricity technologies are coal CCS, nuclear and wind. All the low-carbon model runs have substantial quantities of each of these technologies by 2050, indicating that their costs are broadly comparable and that each of them is required for a low-carbon energy future for the UK. The policy implications are clear: all these technologies should be developed.

The development of each of these technologies to the required extent will be far from easy. Most ambitious in terms of the model projections is probably coal CCS, which is taken up strongly from 2020 to reach an installed capacity of 12 GW by 2035 in CSAM and 37 GW in 2035 in CLC (the residual emissions from coal CCS are a problem in the most stringent scenarios). At present, even the feasibility of coal CCS has not yet been demonstrated at a commercial scale. There would seem to be few greater low-carbon policy priorities than to get such demonstrations on the ground so that commercial CCS can be deployed from 2020 (as the MARKAL model currently assumes). However, the required mechanism has yet to be agreed, nor has the source been identified of the very considerable funds that will be required, and possible technical issues remain unresolved. The timescale for near-term CCS deployment is therefore beginning to look extremely tight. The availability and uptake of CCS as projected by the model runs are therefore optimistic.

The UK Government believes that energy companies should be able to build new nuclear power stations with appropriate regulatory and planning risk streamlining. However, the underlying investment costs, and expectations of future electricity and carbon prices are all matters of considerable uncertainty. The scenarios envisage later deployment of significant investment in new nuclear plant (4 - 30 GW from 2035). The 2035 carbon prices in these scenarios could provide the kind of price required for these investments, but crucially provided that the new generation of nuclear plants are economically and technically proven by about 2015.

It is only in the third area of low-carbon energy supply, renewables, that the UK Government has firm targets for deployment, in the form of the 15% of final energy demand (probably requiring around 35% of electricity) to come from renewables by 2020 in order to comply with the EU's overall 20% target by that date. This amounts to a ten-fold increase in the share of renewables in UK final energy demand in 2006.

In the MARKAL scenarios, only 15% of electricity is generated from renewable sources by 2020, and this is if the levels envisaged in the Renewables Obligations are attained, with current uptake much lower than envisaged. Even with 15% renewable electricity, the maximum share of renewables in 2020 final energy demand (also including transport and heat in buildings) is well short of 15%. There is therefore a very great policy challenge to increase the deployment of renewables over the next ten years. It is worth noting that the slow development of UK renewables to date seems to have been due to non-price issues notably planning and grid access problems. These 'non-economic' problems are not likely to be easy to resolve.

The policy analysis here has focused on the scenarios with increasing carbon targets. The model runs show a marked difference in technology choice in respect of both vehicle technology and biomass use. The policy message is that there is a wide range of developing vehicle technologies, and technologies in other sectors, which become preferred depending on the carbon abatement pathway. It should be the objective of policy at this relatively early stage to ensure that the full range of technologies has the opportunity to develop.

4. THE MACRO-ECONOMIC COSTS OF CLIMATE CHANGE MITIGATION

Because low-carbon technologies are currently more expensive than their high-carbon counterparts, there will be a cost incurred by the kind of large-scale decarbonisation described above, and the reported welfare costs are not insignificant. To estimate these costs in terms of losses of GDP requires the use of a macroeconomic model.

There have been many modelling exercises that have sought to estimate the GDP costs of decarbonisation. Figure 4.1 illustrates the results of a meta-analysis of these modelling exercises, where the different symbols show the runs from various modelling comparison efforts, and each dot gives the result of a particular run within the set. While there are some outliers, it can be seen that the majority of the runs estimate that an 80% reduction in carbon emissions, such as was modelled in the CAM run in Section 3, would cost between 1% and 4% of GDP. Indeed, this was the evidence that caused the Stern Review to conclude that the GDP cost of large-scale decarbonisation would most likely cost around 1% of GDP by 2050 (Stern 2007, p.267).

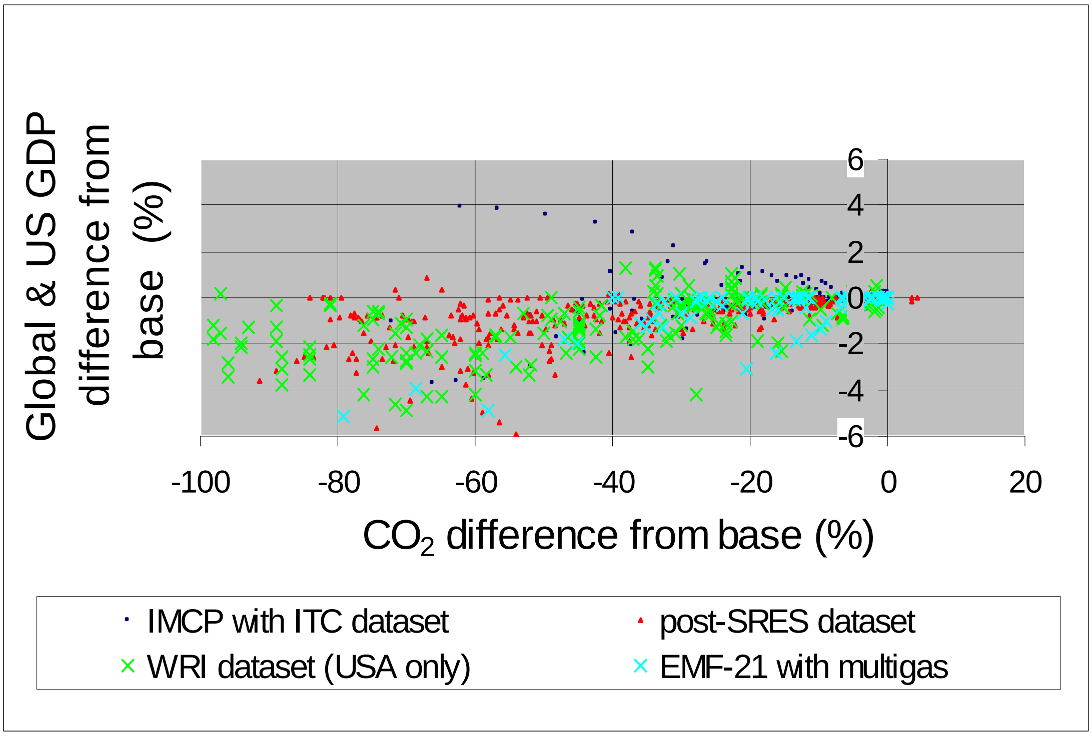


Figure 4.1: Scatter Plot of Model Cost Projections
Source: Barker et al. 2006, cited in Stern 2007, p.270

The differences between the cost estimates reflect a range of different perceptions. The costs are lower depending on the extent to which models incorporate the following assumptions:

- ‘Costs’ are really investments, which can contribute to GDP growth

- There are considerable opportunities for zero-cost mitigation, especially in energy efficiency technologies
- A number of low-carbon technologies are (nearly) available at low incremental cost over the huge investments in the energy system that need to be made anyway
- Climate change policies can spur innovation, new industries, exports and growth
- ‘Learning curve’ experience suggests that the costs of new technologies will fall dramatically

An illustration of this last point is given in Figure 4.2, which shows the cost reductions that have been experienced by a range of technologies as they have been more widely deployed. Such cost reductions as a function of the cumulative production (or sales) of a particular technology are called ‘learning curves’ or ‘experience curves’. In its work on learning curves, IEA (2000) stresses the importance of measures to encourage niche markets for new technologies as one of the most efficient ways for governments to provide learning opportunities.

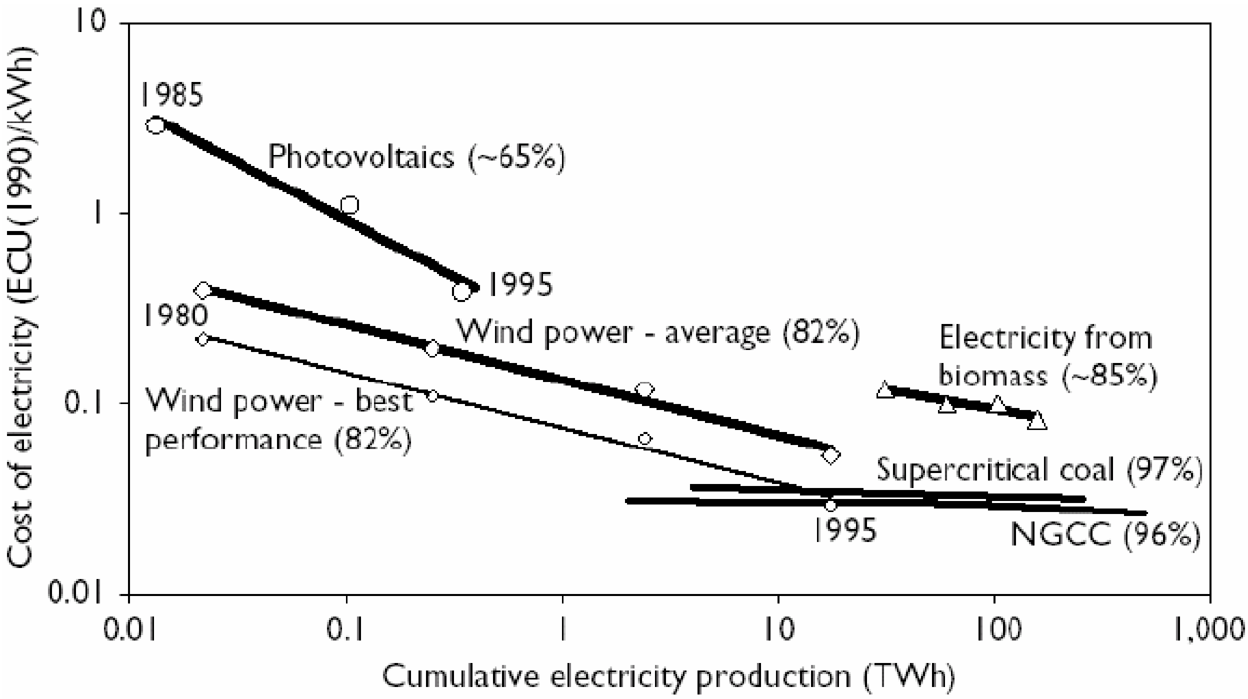


Figure 4.2: Learning curves for various technologies
Note: the figures in brackets refer to the percentage cost reductions after each doubling of installed capacity.
Source: IEA 2000, p.21, cited in Stern 2007, p.254

5. CONCLUSIONS

Attaining the 2^{o}C target or anything near it will require major developments in low-carbon technologies right along the innovation chain (research, development, demonstration, diffusion). At present many of these technologies are little more than niches, and technological transition theories suggest that, if they are to displace fossil fuels as major energy carriers, the technological development will have to be accompanied by supportive economic, social, cultural and political circumstances. These circumstances will need both to bring about, and to be sustained by, a wide range of ambitious and transformational policies, which will in turn need to provide a favourable context for huge investments.

The International Energy Agency, in its 2008 *Energy Technology Perspectives* (IEA 2008) estimates that moving to a global low-carbon energy system will require additional investment (over and above business as usual developments) of USD 45 trillion, or 1.1% global GDP, between now until 2050 (IEA 2008, p.39, of which buildings and appliances will require USD 7.4 trillion, the power sector USD 3.6 trillion, the transport sector USD 33 trillion and industry USD 2.5 trillion.

Under current economic arrangements, it seems likely that it will be the private sector that is expected to furnish most of this investment, but the investment will only be forthcoming if it is profitable. Much enhanced government funding of research, development and demonstration of low-carbon technologies must be put in place, but demonstration and diffusion can only be driven at scale by markets. This seems likely to require immediately significant carbon prices, which rise substantially over the next half century, to choke off investment in high-carbon technologies and incentivise low-carbon investments. These high carbon prices will also greatly change lifestyles and consumption patterns. Provided that the world goes cooperatively in this direction, there are enormous profits to be made from these high carbon prices and changing consumptions patterns. However, technological and policy uncertainty mean that the risks are also high

The overall conclusion of this paper is that the innovation potential exists for a transition to a low-carbon energy system to be technologically and economically feasible, but it requires sustained, wide-ranging, and radical policy interventions to bring about a low-carbon technological revolution and change lifestyles. There are already many examples of these necessary interventions being resisted by affected economic sectors (for example, the producers of fossil energy), and households who want to keep current lifestyles (for example, in relation to transport), or attain Western lifestyles for the first time. In the face of this resistance, politicians may not be able to bring about a low-carbon technological transition before the onset of runaway climate change.

REFERENCES

Adamson, K.-A. 2005 'Calculating the price trajectory of adoption of fuel cell vehicles', *International Journal of Hydrogen Energy*, Vol.30, pp.341-350

Anandarajah, G., Strachan, N., Ekins, P., Kannan, R. & Hughes, N. 2008 'Pathways to a Low-Carbon Economy: Energy systems modelling', UKERC Energy 2050 Research Report 1, Ref. UKERC/RR/ESM/2008/03, November, UKERC, London, http://www.ukerc.ac.uk/

Arthur, W.B. 1988 'Competing Technologies: an Overview' in Dosi, G., Freeman, C., Silverberg, G. & Soete, L. (Eds.) *Technical Change and Economic Theory*, Frances Pinter, London, pp.590-607

Barker, T., Qureshi, M. & Köhler, J. 2006 'The costs of greenhouse gas mitigation with induced technological change: A meta-analysis of estimates in the literature', mimeo, Cambridge Centre for Climate Change Mitigation Research (4CMR), University of Cambridge, Cambridge

Berkhout, F., Smith, A. & Stirling, A. 2003 'Socio-technological Regimes and Transition Contexts', Paper No.106, September, SPRU, University of Sussex, Brighton

BMU/UBA (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit and Umweltbundesamt) 2007 *Umweltwirtschaftsbericht 2007*, BMU/UBA, Berlin

Carbon Trust 2002 Submission to Energy White Paper Consultation Process, Carbon Trust, London

David, P. 1985 'Clio and the Economics of QWERTY', *American Economic Review*, Vol.76, pp.332-337

Edgerton, D. 2006 *The Shock of the Old: Technology in Global History since 1900*, Profile Books, London

ETF (Environmental Transformation Fund) 2008 'UK Environmental Transformation Fund: Strategy', Departments of Business Enterprise and Regulatory Reform (BERR), Environment, Food and Rural Affairs (DEFRA), and Innovation, Universities and Skills (DIUS), London, http://www.berr.gov.uk/files/file47575.pdf

Foxon, T. 2003 *Inducing Innovation for a Low-Carbon Future: Drivers, Barriers and Policies*, a report for the Carbon Trust, July, Carbon Trust, London

Freeman, C. & Louça, F. 2001 *As Time Goes By*, Oxford University Press, Oxford

Frontier Economics 2009 'Alternative Policies for Promoting Low Carbon Innovation', July, Report for Department of Energy and Climate Change (DECC), DECC, London, http://www.decc.gov.uk/en/content/cms/publications/lc_trans_plan/lc_trans_plan.aspx

Geels, F. 2002a *Understanding the Dynamics of Technological Transitions*, Twente University Press, Enschede NL, published in revised form as Geels 2005

Geels, F. 2002b 'Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study', *Research Policy*, Vol.31, pp.1257-1274

Hughes, T. (1987) 'The evolution of large technological systems' in Bijker, W., Hughes T. & Pinch, T. (Eds.) 1987 *The Social Construction of Technological Systems: New Directions in the Sociology and History of* Technology, MIT Press, Cambridge MA, pp.51-82

IEA (International Energy Agency) 2000 *Experience Curves for Energy Technology Policy*, IEA, Paris

IEA (International Energy Agency) 2008 *Energy Technology Perspectives: Strategies and Policies to 2050*, IEA, Paris

ISC (International Scientific Congress 'Climate Change: Global Risks, Challenges and Decisions') 2009 *Synthesis Report*, March, University of Copenhagen, Copenhagen, http://climatecongress.ku.dk/, accessed October 22 2009

Kannan R., and Strachan N, 2008, Modelling the UK residential energy sector under long-term decarbonisation scenarios: Comparison between energy systems and sectoral modelling approaches, *Applied Energy*, 86 (4), pp.416-428, Doi:10.1016/j.apenergy.2008.08.005

Kannan R., Strachan N., Pye S., and Balta-Ozkan N., 2007, UK MARKAL model documentation. http://www.ukerc.ac.uk/

Kemp, R. & Foxon, T. 2007 'Eco-innovation from an innovation dynamics perspective', Deliverable 1 of MEI project, April, UNU-MERIT, Maastricht, available at http://www.merit.unu.edu/MEI/deliverables/MEI%20D1%20Eco-innovation%20from%20an%20innovation%20dynamics%20pespective.pdf

Kemp, R. & Rotmans, J. 2001 'The management of the co-evolution of technical, environmental and social systems', international conference Towards Environmental Innovation Systems, Garmisch-Partenkirchen, September

Kemp, R., Schot, J. & Hoogma, R. 1998 'Regime Shifts to Sustainability through Processes of Niche Formation: the Approach of Strategic Niche Management', *Technology Analysis and Strategic Management*, Vol.10, pp.175-196

Kline, S.J. & Rosenberg, N. 1986 'An Overview of Innovation', in Landau, R. & Rosenberg, N.
(Eds) 1986 *The Positive Sum Strategy*, National Academic Press, Washington DC

Krozer, Y. 2002 *Milieu en innovatie* (Environment and innovation). PhD Thesis, Groningen University, http://irs.ub.rug.nl/ppn/241947103

Mokyr, J. 2002 *The Gifts of Athena: Historical Origins of the Knowledge Economy*, Princeton University Press, Woodstock (GB)

McDonald, A., and Schrattenholzer, L. 2001 'Learning rates for energy technologies', *Energy Policy* 29, p. 255-261.

Nelson, R. & Winter, S. 1982 *An Evolutionary Theory of Economic Change*, Bellknap Press, Cambridge MA

Rip, A. & Kemp, R. 1998 'Technological Change' in Rayner, S. & Malone, E. (Eds.) *Human Choice and Climate Change*, Vol.2, Battelle Press, Columbus OH, pp.327-399

Schumpeter, J. 1942 *Capitalism, Socialism and Democracy*, 1976 edition, George Allen & Unwin, London

Socolow, R., Hotinski, R., Greenblatt, J. & Pacala, S. 2004 'Solving the Climate Problem: Technologies Available to Curb CO Emissions', *Environment*, December, pp.8-19

Stern N. 2007 *The Economics of Climate Change: The Stern Review*, Cambridge University Press, Cambridge

Strachan N., and Kannan R., 2008, Hybrid modelling of long-term carbon reduction scenarios for the UK, *Energy Economics*; 30(6): 2947-2963.

Strachan N., Kannan R. and Pye S., 2008a, *Scenarios and Sensitivities on Long-term UK Carbon Reductions using the UK MARKAL and MARKAL-Macro Energy System Models*, UKERC Research Report 2, http://www.ukerc.ac.uk/

Strachan N., Pye S., and Hughes N., 2008b, The role of international drivers on UK scenarios of a low carbon society, *Climate Policy*, 8, S125-S139.

Strachan N., S. Pye S. and R. Kannan R. 2009a, The Iterative Contribution and Relevance of Modelling to UK Energy Policy, *Energy Policy*, 37 (3), 850-860

Strachan N., Balta-Ozkan N., Joffe D., McGeevor K., and Hughes N., 2009b, Soft-linking energy systems and GIS models to investigate spatial hydrogen infrastructure development in a low carbon UK energy system, *International Journal of Hydrogen Energy*, 34 (2) 642-657

Wallace, D. 1995 *Environmental Policy and Industrial Innovation: Strategies in Europe, the US and Japan*, Earthscan, London

Wessner, C. 2005 'Driving Innovations across the 'Valley of Death'', *Research-Technology Management*, Vol.48 No.1, January-February 2005, pp. 9-12