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**Challenges of the Transition to a Low Carbon, More Electric Future:
From Here to 2050**

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1. Introduction

Electricity generation presently contributes approximately 30% of United Kingdom (UK) carbon dioxide (CO₂) emissions (Alderson *et al.*, 2012; POST, 2007), the principal ‘greenhouse gas’ (GHG) having an atmospheric residence time of about 100 years (Hammond, 2000). This share mainly arises from the use of fossil fuel (coal and natural gas) combustion for this purpose. Changes in atmospheric concentrations of GHGs affect the energy balance of the global climate system. Human activities have led to quite dramatic increases since 1950 in the ‘basket’ of GHGs incorporated in the Kyoto Protocol; concentrations have risen from 330 ppm to about 430 ppm currently (IPCC, 2007). Prior to the first industrial revolution in the 18th Century the atmospheric concentration of ‘Kyoto gases’ was only some 270 ppm. The cause of the observed rise in global average near-surface temperatures over the second half of the 20th Century has been a matter of dispute and controversy. But the most recent (2007) scientific assessment by the Intergovernmental Panel on Climate Change (IPCC) states with ‘very high confidence’ that humans are having a significant impact on the global warming (IPCC, 2007). They argue that GHG emissions from human activities trap long-wave thermal radiation from the Earth’s surface in the atmosphere (not strictly ‘greenhouse’ phenomena), and that these are the main cause of rises in climatic temperatures. In order to mitigate anthropogenic climate change, the *Royal Commission on Environmental Pollution* in the UK (RCEP, 2000) recommended at the turn of the Millennium a 60% cut in UK CO₂ emissions by 2050. The British Government subsequently set a tougher, legally binding target of reducing the nation’s CO₂ emissions overall by 80% by 2050 in comparison to a 1990 baseline (DTI, 2007; Climate Change Act 2008).

A number of observers have studied the way in which the world has undergone a transition over time between various energy sources. These cycles, or Kondratieff long-waves (Nakicenovic, 1998; Matias and Devezas; 2007), are illustrated in terms of world primary energy shares in Fig. 1 (Hammond and Waldron, 2008), along with future projections out to 2050 according to the Shell ‘*Dynamics as Usual*’ Scenario (Davis, 2001). ‘Traditional’

energy sources include animal manure, fuel wood, charcoal, water wheels, and windmills. Over the next 40 years or so there is likely to be a major growth in energy demand, resulting principally from the development of rapidly industrialising countries (such as China and India). The depletion of finite fossil fuel resources like oil and natural gas, and the need for climate change mitigation, will therefore require a portfolio of energy options: energy demand reduction and energy efficiency improvements, carbon capture and storage (CCS) from fossil fuel power plants, and a switch to other low or zero carbon energy sources: various sorts of renewables (including bioenergy and biofuels) or nuclear power (see Fig. 1).

The history of electricity generation since the time of Edison has been based around the concept of employing large, centralised power stations (see, for example, Hughes, 1983; Buchanan, 1994; Hammond, 2000; Pearson and Watson, 2012). Thus, the bulk of electricity in Britain is still generated by large thermal power plants that are connected to a high-voltage transmission grid, and is then distributed to end-users via regional low-voltage distribution networks (Bolton and Foxon, 2011; POST, 2007; Hammond and Waldron, 2008). The whole UK energy system is represented schematically in Fig.2 (Hammond, 2000), where the electricity network is clearly illustrated. This centralised model has delivered economies of scale and reliability (Alderson *et al.*, 2012), but there are significant drawbacks. The UK Electricity Supply Industry (ESI), for example, currently has a heavy reliance on primary fuels, particularly coal and natural gas. Much of the electricity grid was constructed in the 1950s and 1960s. It is therefore heavily reinforced in former coal-mining areas, and is nearing the end of its design life (DTI, 2003; Hammond and Waldron, 2008). There are 'bottlenecks' restricting power flow from Scotland to England (2.2GW_e), and via the interconnectors (in the form of high-voltage undersea cables) to France, Northern Ireland and the Netherlands (POST, 2007). The grid will require not only renewal but also reconfiguration in order to accommodate distributed generation.

Cheap coal from overseas is unlikely to cause a security of supply problem, but the increasing reliance being placed on imports of natural gas for *Combined Cycle Gas Turbine* (CCGT) power plants brings with it potential risks. Britain became a net importer of natural gas in 2004 as reserves in the UK continental shelf declined (DTI, 2003; Hammond and Waldron, 2008; DECC, 2012). In the long-term there is considerable uncertainty about the security of imported gas supplies (Hammond and Waldron, 2008). The largest natural gas reserves globally are found in Russia, North Africa, and the Middle East. Even without the obvious political problems associated with these regions, there will be difficulties in terms of the transportation of gas from these areas. Long pipelines, additional port and storage capacity will all be required. The natural gas interconnector between Norfolk (in the East Anglian region of England) and Belgium means that gas can flow out of Britain to the continental market, as well as inward to meet domestic demand. Other gas interconnectors link the UK with Norway and the Netherlands. Gas imports are likely to continue to grow quite rapidly in the near future (Alderson *et al.*, 2012).

Achieving the UK carbon reduction target of 80% by 2050 will mean a transition in the systems for producing, delivering and using energy that is not only low carbon, but also secure and affordable, thus resolving the energy policy 'trilemma'. A recent independent

review (Hills 2012) confirmed, however, that fuel poverty is a serious national problem in the UK and suggested that it is set to rise rapidly, adding a further affordability challenge to the resolution of the trilemma.

A consortium of partners from nine university institutions was established under the auspices of research funding via a strategic partnership between *E.On UK* (the electricity generator) and the UK *Engineering and Physical Sciences Research Council* (EPSRC), to study the role of electricity within the context of '*Transition Pathways to a Low Carbon Economy*' [under Grant EP/F022832/1]. This team was made up of UK engineers, social scientists, policy analysts and innovation specialists. It has sought to develop and explore three 'transition pathways' towards a UK low carbon electricity system (Foxon *et al.*, 2010; Foxon, this Section), to understand the changing roles of large and small 'actors' in the dynamics of these transitions, and to learn from the successes and failures of past transitions. They have focused on the choices and actions needed to 'get there from here', and on the analysis of the pathways' technical, socio-economic and environmental implications. An innovative, robust, and 'whole systems' evidence base has therefore been developed that is distinctive from those devised elsewhere in the UK energy research community. The pathways are not predictions or roadmaps; rather they are a way of imaginatively exploring future possibilities, to inform proactive and protective decision making and enhance the potential for building consensus towards common goals. They form the basis for most of the contributions in this Special Section of the journal *Energy Policy*. Three additional papers were invited in order to give a continental European (Dijk *et al.*, this issue; Verbong *et al.*, this Section) and an industrial (Boston, this Section) perspective respectively.

2. Pathways, Historical Lessons for Energy System Governance, and Uncertainties

The starting point in the development of the current UK transition pathways (Foxon *et al.*, 2010; Foxon, this Section), unlike many scenario-building exercises, is that the governance framings or 'logics' of key actors will be a crucial influence on any pathway towards a future low-carbon, UK energy system. Stakeholder workshops were employed by the consortium to distinguish the logics of three core sets of actors: those of the market, government and civil society. Consequently, the three transition pathways were named *Market Rules* (MR), *Central Co-ordination* (CC) and *Thousand Flowers* (TT); each being dominated by a single group's logic. The paper by Foxon (this Section) builds on the earlier one by Foxon *et al.* (2010) in order to summarise the development and high-level analysis of the present transition pathways set, in order to explain their key features and the distinctiveness and value of the approach; the approach builds *inter alia* on approaches originally devised by Dutch researchers (e.g., Geels, 2002; Rip and Kemp, 1998). Thus the consortium applied a multi-level perspective for analysing socio-technical transitions, based on interactions at and between three levels: *niche innovations*, *socio-technical regimes*, and *macro-landscape pressures* [see Fig. 3 (Foxon *et al.*, 2010)]. The pathways use an 'action space' concept [originally developed by consortium members Jacquie Burgess and Tom Hargreaves (private communication, 2010)] to explore the dynamic interactions between choices made by actors. Foxon (this Section) summarises the key technological and institutional changes associated with these pathways, and the roles of actors in bringing them about. This leads to an

identification of the key risks to the realisation of each of the pathways, and of the challenges for individuals, businesses, social movements and policy-makers in taking action to bring them about and sustain them. The MR and CC pathways show two main risks and uncertainties. On the one side lie the technical, economic and financial challenges of delivering the large-scale low carbon generation technologies (such as fossil fuelled power plants with CCS, nuclear power and offshore wind) and the grid enhancements to support them. On the other lies the uncertainty of whether concerns about security of supply and climate change would outweigh public resistance to the nature and costs of any or all of these technologies. But in the TT pathway the main uncertainties relate to the technical and economic feasibility of locally distributed generation technologies, and to the realisation of the behavioural, organisational and technological changes needed to achieve and sustain the high levels of energy demand reduction that characterise this pathway. This, of course, is the pathway for which Britain has least prior experience on which to draw.

The present transition pathways consortium has sought to learn from past socio-technical transitions in order to help explore future transitions and what might enable or avoid them. Early analysis by Bennett and Pearson (2009) studied the potential for renewable raw materials (RRM) to substitute fossil hydrocarbons in synthetic products via a case study of the transition from coal-based to petrochemical feedstocks in the UK (1921-1967). There they employed a system dynamics approach to extract and elucidate the key interrelationships between technologies, policy and society. In a similar vein, Chalmers *et al.* (2009) examined several major UK energy transitions in order to draw out lessons for the development of CCS power plant in the context of the UK Government-sponsored competition at that time. They examined the post-World War II development of nuclear electricity, the increase in size of pulverised coal power stations in the decade around 1960, the opening up of North Sea oil and natural gas fields in the 1960s and 1970s, and flue gas desulphurisation in the late 1980s and 1990s. These historical transition studies provided a number of insights into critically important underpinning actions: the requirement for the sort of financial incentives for CCS deployment, the importance of active public engagement, together with the desirability of reviewing skills and capacity requirements (Chalmers *et al.*, 2009). The CCS competition for the first UK demonstrator is now recognised to have been a failure (NAO, 2012), after several of the initial bidders dropped out and the Government withdrew from negotiations with the last remaining bidder in October 2011. It is being succeeded by another CCS competition that will (hopefully) take account of past lessons (Chalmers *et al.*, 2009; Hammond *et al.*, 2011b; NAO, 2012).

The paper by Arapostathis *et al.* (this Section) illustrates again the co-evolution of technologies, infrastructures and institutions, the power of incumbents, and the complex challenges of rapidly scaling-up new technologies. Their first case study covers the market-led transformation of the manufactured gas regime from 1877 to 1914, which extended the end-uses of gas beyond lighting to include cooking, and among the working classes as well as the middle classes. The second case further reconstructs the transition from town gas to natural gas over the period from 1948 to 1977. This state-led and co-ordinated conversion to natural gas was preceded by a period of destabilisation of the manufactured gas regime, the co-existence of several *niche* technologies and the hybridisation of the key actors and technological

infrastructures of the incumbent regime. Comparing these cases provides insights for future energy service transitions by addressing the significance of power, trust and networking in the decision making processes involved in the governance of energy transitions. Arapostathis *et al.* (this Section) suggest that while multi-actor, market-led transitions offer valuable chances for experimentation and novelty, government-led transitions with fewer actors and more centralised decisions may be easier to achieve. This helps to explain why recent governments have moved towards a hybrid pathway with greater government involvement in a broadly market-dominated system, though achieving an appropriate balance between centralised and market approaches and involving civil society in decision-making remain significant challenges.

Pearson and Watson (2012) recently adopted this approach of historical analysis to study the lessons to be learnt for UK energy policy from experiences over the nearer term: 1980-2010. Over these three decades there have been major shifts away from coal and towards natural gas in the power sector and industry, as well as a switch from the UK being a net energy importer to net exporter and back again. The structure and governance of the energy industries has undergone profound change (Pearson and Watson, 2012). The role of the British Government has been much diminished with the advent of private sector ownership and forms of competition in industries that were hitherto dominated by state-owned, 'natural monopolies'. Pearson and Watson (2012) draw attention to three challenges that confront UK energy policy: first, history reinforces the scale of ambition associated with the low carbon transition, which might make the UK privatisation and liberalisation processes seem to be relatively straightforward; second, because energy policy is not confined to the domain of the energy department within government, successful policy co-ordination will be essential; and third, the low carbon transition will be full of tensions which policy will need to address, not only in relation to the familiar tensions between objectives but also to the relative contributions of centralised, top down, large-scale action and decentralised, bottom up smaller scale initiatives.

In a recent *Energy Policy* Special Section, Fouquet and Pearson (2012) describe insights for the analysis of prospective transitions from research into past transitions, by international contributors who met at a 2011 Cardiff workshop initiated by the Transition Pathways project. In that Section, Pearson and Foxon (2012), explore recent suggestions that a low carbon transition offers challenges and might yield economic benefits comparable to those of previous industrial revolutions. They explore the factors that enabled and sustained past industrial revolutions, and the role of 'general purpose technologies' in them. They conclude that while achieving a low carbon transition may require societal changes on a scale comparable with those of previous high carbon industrial revolutions; this transition does not yet resemble them. They propose, however, that while appropriate government intervention, consistent and coherent carbon pricing and support for innovation might create incentives analogous to some of those that drove the First Industrial Revolution, an accelerated and different form of revolution would be needed to meet the urgent needs of climate stabilisation.

Low carbon transition pathways analysis inevitably involves a consideration of the uncertainties surrounding future technological and social changes. The paper by Hughes *et al.*

(this Section) argues that such uncertainties can be better understood, and the strategic and policy effectiveness of various futures (pathways or scenarios) thereby improved, through a systematic categorisation of their different certain and uncertain elements. It builds on a recommendation from an earlier review of low carbon scenarios (Hughes and Strachan, 2010) that a clearer identification of the activities of system actors within scenarios will make these activities more easily managed or controlled for the purpose of strategic policy making. Both Foxon *et al.* (2010) and Hughes and Strachan (2010) criticised the lack of actor specification in low carbon pathways and scenarios. Hughes *et al.* (this Section) therefore propose a system conceptualisation that is based on a detailed description of the dynamics of the actors and institutions relevant to the system under study. They argue that this should be iteratively linked to a detailed representation of the technological system, and that it should consequently be possible to characterise the future elements of the system as being either predetermined, actor contingent or non-actor contingent. It emerges that the different categories of future element are associated with different types of uncertainty, e.g., extreme external (or *landscape*) pressures [see Fig. 3] and potential socio-technical lock-in. Each of these uncertainties prompts different strategic policy responses. Hughes *et al.* (this Section) believe that this categorisation of future elements clarifies the relationship of the energy scenario content and specific types of policy response, and may ultimately aid the policy relevance of the resulting low carbon transition pathways.

3. The Supply Side, Networks and Smart Controls

In the first of the invited papers, Boston (this Section) provides an industrial viewpoint piece that examines the issues surrounding security of supply of the power system. He suggests that security of supply has received less attention than the other aspects of the energy policy ‘*trilemma*’ (see Section 1 above). Threats to electricity supplies operate over a continuum of timescales, from long-term events that generally operate over years to medium-term events that occur in the domain of traded markets, and short-term events that are less than an hour and are therefore within gate closure of many markets. Boston notes that Hammond and Waldron (2008) used an online survey amongst a wide range of stakeholders to identify and rank risks according to likelihood and consequence, and that many of their high-scoring risks appear as long to medium-term threats in his analysis, or as underlying causes of these threats. Boston (this Section) looks at how threats and mitigation measures can be classified in terms of where they act on the supply chain and the timescale over which they act. Only by considering the full range of timescales from seconds to decades can the full picture emerge of the effects of new technologies on security of supply. A brief examination of major power sector blackouts *worldwide* over the past 40 years (Boston, this Section) shed light on the causes of supply failures, and helped identify the most vulnerable parts of the supply chain. In order to be included in the study, any blackout had to cause a loss of supply of at least one million customer-days and there had to be sufficient information to categorise the event. Weather was found to be the most important primary cause of blackouts, with storm damage to the transmission system causing half the failures. Other notable weather effects were drought (loss of cooling water) and ice build-up on transmission lines. Some of these, particularly the droughts in France and ice storms in Canada, are specific to certain systems

and areas rather than being universal threats. The next leading cause of incidents was the lack of maintenance or asset replacement: a risk that was also ranked as the second highest in the online stakeholder appraisal undertaken by Hammond and Waldron (2008). Three of the blackout events identified by Boston (this Section) were associated with failures of cables which were past their expected life or were more heavily loaded than originally intended. The network was consequently found to be the most vulnerable part of the electricity supply chain; reinforcing the case for grid renewal and reconfiguration in the UK (Alderson *et al.*, 2012; Hammond and Waldron, 2008).

The *intermittency* and *inflexibility* of low-carbon generation mean that fossil-fuelled generation must be replaced to a greater extent than suggested by annual average figures, if required carbon reductions are to be achieved. The *electric vehicle (EV) market* may lead to a rapid growth that could bring significant changes to power system demand patterns and operation. Likewise, the transition pathways postulate increased electrification of transport and heating, which could result in greater *peak demands* on the network that would be disproportionately higher than the increase in energy consumption. Significant generation, transmission and distribution network reinforcements (operating with much lower utilisation factors) will be needed, including tens of billions of pounds of distribution network investment. However, a co-ordinated application of smart demand technologies, such as smart EV charging, smart heat pump control and active distribution networks with the use of voltage regulators can significantly reduce network reinforcement costs (Pudjianto *et al.*, this Section).

Two modelling tools have been combined in the work reported by Barnacle *et al.* (this Section) to assess the robustness of the three transition pathways in terms of generation and infrastructure requirements. Here the *Future Energy Scenario Assessment* (FESA) tool (see also Barton *et al.*, this Section) is used to develop pathway specific large-scale generation mixes that meet expected demands on both a yearly and hourly time-step basis. This hourly modelling indicates massive requirements for peaking plant or energy storage, even after the optimistic application of automated demand-side flexibility. The *Multi-Objective Transmission Reinforcement Planning* (MOTRiP) tool has been used to generate a population of 100 electricity network reinforcement plans. The key trade-offs are described, and the best reinforcement plan determined for the MR pathway 2020 generation mix. Barnacle *et al.* (this Section) show that a third (34%) of the reduction in operational or ‘stack’ CO₂ emissions on that timescale can only be achieved if the network is reinforced to allow this via the provision of adequate network capacity. Their work has also sought to ensure security against thermal overloading and other contingencies, through a combination of the ‘full’ temporal analysis produced by FESA and the comprehensive geographical analysis that MOTRiP provides. Consequently these models yield a high-quality holistic examination of the pathways, and thereby determine the need for national infrastructure reinforcements with future changes in demand and generation patterns.

Electrification of transport fleets and heating sectors (as indicated above) is seen as one of the key strategies to further reduce the use of fossil fuels and the resulting GHG emissions.

However, it will potentially cause a significant increase of electricity peak demand, as Barnacle *et al.* (this Section) show, and have adverse consequences for the electricity system. The paper by Pudjianto *et al.* (this Section) suggests that the adoption of electric heating and EVs under all three transition pathways will increase peak electricity demand in the UK by 2-3 times up to 2050. This will particularly impact on distribution networks. They argue that massive distribution network reinforcement will be required, costing up to £36 bn over the period 2010-2050. Consequently, Pudjianto *et al.* (this Section) address the benefits of various applications of 'smart' network control and demand response technologies for enhancing the integration of future load categories, and for improvements in operation management and efficient use of distribution network assets. A range of numerical simulations have been employed on different distribution network topologies (rural and urban networks) to identify the need and the cost of network reinforcement required to accommodate future load under various operating strategies such as *Business as Usual* (passive demand and passive network) against the smart grid approach. Pudjianto *et al.* studied applications of smart Plug-in Vehicle (PiV) charging, smart heat pumps, and optimised control of network voltage regulators to reduce network investment. They advocate the revision of network planning and design standards. *Distribution Network Operators* (DNOs), for example, need to be incentivised to take advantage of smart control solutions as an alternative to strengthening the grid. But recently Bolton and Foxon (2011) charted the 'co-evolution' between technologies and institutions in electricity distribution networks since the introduction of privatization and market liberalization over twenty years ago. They observed that efforts to promote radical and 'architectural' innovation, such as the transition to a smart grid, face significant barriers at the firm and sector levels.

4. The Demand Side

The *demand for energy at the building scale* arises from a multiplicity of lifestyles, behaviours, service needs, end-use devices, the building fabric and local energy conversion/storage. There is potential for emissions mitigation in all of these facets, and many opportunities exist to reduce the energy needed to satisfy basic energy services in existing and new build stock over the transition period. Over the last few years (Torriti *et al.*, 2010), load growth, increases in intermittent generation, declining technology costs, and the increasing recognition of the importance of customer behaviour in energy markets have brought about in Europe a change in emphasis towards *Demand Response* (DR). Torriti *et al.* (2010) suggest that, while business programmes, technical and economic potentials vary across Europe, co-ordinated DR policies have been slow to emerge. They argue that this is because of the limited knowledge on DR energy saving capacities, high cost estimates for DR technologies and infrastructures, and policies focused on creating the conditions for liberalising the EU energy markets. But a shift away from fossil fuels as a result of the electrification of transport is evident in all of the present transition pathways, as is growth in the use of electricity for heating, via heat pumps.

Barton *et al.* (this Section) explore the possible evolution of UK electricity demand as it moves along the three transition pathways. Detailed modelling of hourly balancing of these demands was undertaken using the FESA tool (see Section 3 above). These studies provided an important component of the ‘technical elaboration’ of the transition pathways narratives (Foxon *et al.*, 2010; Foxon, this Section). [An appendix (Barton *et al.*, this Section) provides an outline of the physical basis of the FESA tool, its limitations, its location within the range of alternative energy systems models, and a description of the methods employed for FESA validation.] Demand balancing was found to represent a significant challenge. The MR pathway, for example, sees continued growth in absolute levels of electricity use, despite continued technical improvements in appliances and building fabric; peak demands also grow, to some 83GW by 2050. Enhanced energy efficiency contributes to lower trends in the CC and TT pathways, and greater use of non-electricity sources for heating, notably CHP, in TT drives demand down further, such that peak demand is only 38GW. However, this reduction comes at a price, with significant ‘excess’ generation locally at times of low electricity demand, as CHP follows heat demands, exacerbating the problem of low capacity factors for central generation caused by growth in the role of intermittent renewables. A variety of ‘demand side participation’ (DSP) measures have been modelled (Barton *et al.*, this Section) in order to determine whether the need for conventional generation with very low capacity factors can be minimised. DSP is found to yield significant benefits in this regard. Load shifting, for example, is shown to address this problem effectively, but will require widespread acceptance of the automatic control of appliances and/or ‘deep’ behavioural changes. Lastly, Barton *et al.* (this Section) display projections for the imports of fossil fuels into the UK and the operational (or ‘stack’) GHG emissions under each of the three transition pathways.

5. ‘Whole Systems’ Energy and Environmental Appraisal

The whole systems appraisal of energy technologies and the transition pathways has been undertaken (Hammond *et al.*, this Section) within an overarching sustainability framework (Hammond and Jones, 2011), together with a set of evaluation criteria for specific energy technologies and pathways. It builds on earlier studies of simpler power networks (El-Fadel *et al.*, 2011) and individual energy technologies (Hammond *et al.*, 2011a). The impact of the three pathways has been assessed using energy analysis and environmental life cycle assessment (LCA) on a ‘whole systems’ basis: from ‘cradle-to-gate’ (Hammond *et al.*, this Section). ‘Whole system’ GHG emissions are the sum of upstream and operational emissions. The latter (‘stack’) emissions are those directly associated with the combustion of fossil fuels within power stations. Thus, the whole system emissions amount to those related to the ‘*Energy Transformation System*’ as defined by way of Fig. 2 above. Hammond *et al.* (this Section) highlight the significance of ‘upstream emissions’ and their (technological and policy) implications, in contrast to the emphasis on power plant operational emissions conventionally presented by other analysts. Upstream environmental burdens arise from the need to expend energy resources in order to extract and deliver, for example, fuel to a power station. They include the energy requirements for extraction, processing/refining, transport,

and fabrication, as well as methane leakages that occur in coal mining activities – a major contribution – and from natural gas pipelines.

The impacts of upstream emissions on the carbon performance of various low carbon electricity generators [such as large-scale combined heat and power (CHP) plant and CCS power stations], and of the pathways themselves distinguish the present findings by Hammond *et al.* (this Section) from those of other UK analysts [such as Barton *et al.* (this Section), the UK Government's *Department of Energy and Climate Change* (DECC), and their independent *Committee on Climate Change* (CCC)]. Hammond *et al.* (this Section) argue that it is not possible fully to decarbonise the UK electricity supply industry by 2030 (as advocated by the CCC), unless the whole economy adopts low carbon energy sources – an unlikely prospect on a 2030 timescale. Neither the CCC or DECC currently account for upstream GHG emissions, or perform their calculations on a 'whole systems' basis of the sort employed by Hammond *et al.* (this Section). They only determine the operational or stack emissions associated with the *Energy Transformation System* (Fig. 2).

If the UK is to genuinely meet its stringent carbon reduction targets, then it will therefore be necessary to account for upstream emissions from power generation of the type evaluated here by Hammond *et al.* Otherwise, even if the current UK carbon reduction targets are met, there will remain further emissions upstream. Taking account of upstream emissions also suggests the striking result that CCS is likely to deliver only about a 70% reduction in carbon emissions on a whole system basis, in contrast to the normal presumption of a 90% reduction (Hammond *et al.*, 2011b). Hammond *et al.* (this Section) finally present estimates of a range of other pollutants or wastes released into the environment as a consequence of the power network (via 17 separate impact indicators, together with a tentative 'single score', aggregate LCA measure). These address issues related to the impacts, for example, of non-renewable energy (NRE) resources, human toxicity, and the health impacts associated with particulate matter formation (PMF).

6. Patterns of Energy Use and Behaviour

In an invited paper giving a continental European perspective, Verbong *et al.* (this Section) analyses practices and perceptions associated with smart grid experiments in the Netherlands. The co-authors work from within the Dutch transitions research community. Thus, for example, Verbong and Geels (2007) analysed the historical dynamics within the Dutch electricity system from 1960 to 2004. There they noted that visions of the future electricity system differ greatly: from the development of a large-scale European *Supergrid* to the construction of local micro-grids. But Verbong *et al.* (this Section) conducted in-depth interviews with the stakeholders of 12 smart grid projects that support the *Dutch Smart Grids* programme, using a '*Strategic Niche Management*' (SNM) framework. These projects still are in an early phase, and so the focus was on the role of users in their design. SNM studies focus on processes that are internal to the development of *niche innovations* (see Section 2 and Fig. 3 above), such as the articulation of expectations and visions, the building of social networks, and learning processes. Verbong *et al.* argue that too much emphasis on the

technological aspects of innovation and their economic incentives can become a barrier to wider understanding. Social variables like daily routines, individual preferences, and social relations in a household have been found to be important for energy demand reduction, including those beneficially influenced by smart meters (as determined, for example, by Hargreaves *et al.*, 2010). This may reflect a co-evolution of technology with social practices, changing routines, and behaviour. Verbong *et al.* (this Section) therefore contend that users, their daily routines, and their social context (e.g., household or community) should be taken more seriously in smart grid experiments. Consequently, they assert that learning about the social dimensions of smart grids, and the international exchange of experiences, can help prevent a premature lock-in into a particular transition pathway and system configuration.

Nye *et al.* (2010) recently argued from psychological and sociological perspectives for the need to consider energy system transitions within a wider context around consumer-oriented lifestyles. They suggested that domestic actors can play an active role in such transitions through establishing new routine and conventional uses of energy in everyday life. Lower carbon technologies, like smart energy meters and micro-generation equipment, can lead to the disruption of unsustainable energy-using routines. Moreover, these devices could help to make energy consumption and energy costs more visible and relevant to the everyday lives of domestic users. In a related field trial (Hargreaves *et al.*, 2010), using qualitative interviews with 15 householders using *Smart Energy Monitors* (SEMs), they highlighted the importance of the social dynamics on household energy use. These researchers explored how SEMs become embedded within household routines and relations and can lead to negotiation and conflict that hinders energy saving efforts, as often as to rational-planning and co-operative steps to cut consumption. They found that households with SEMs rapidly returned to pre-existing energy use levels. Most early adopters used the displays to help picture their household's 'normal' pattern of energy use (Hargreaves *et al.*, 2010), and tended often angrily to resist exhortations from external agencies (government, energy companies, NGOs) to change it.

Here Hargreaves *et al.* (this Section) report a follow-on UK study of how, over a 12-month period, householders interacted with feedback on their domestic electricity consumption in a field trial of real-time displays or smart energy meters. Drawing on the findings of 11 follow-up qualitative interviews with householders involved in a 'Visible Energy Trial', Hargreaves *et al.* (this Section) observe that over time, smart energy meters gradually become 'backgrounded' within normal household routines and practices. They found that the SEMs do increase householders' knowledge of, and confidence about, the amount of electricity they consume, but (beyond a certain level and for a wide variety of reasons) the monitors do not necessarily encourage or motivate householders to reduce their levels of consumption. Finally, Hargreaves *et al.* (2010) suggest that household practices may become harder to change as householders realise the energy saving potential, once equipped with new knowledge and expertise about their levels of electricity consumption. These householders may also become frustrated by the absence of wider policy and market support. The closer engagement of end-users with governance of the energy system in the TT pathway *perhaps* offers one means to overcome these barriers.

Another invited contribution from continental Europe, by Dijk *et al.* (this Section), addresses the emergence of what is termed an ‘electric mobility trajectory’. They note that the *regime* around the internal combustion (IC) engine-driven car has dominated road transport for more than 100 years. This technological lock-in comes, in part, from the production side. It has not been regarded as economically attractive to invest in new automotive power trains that appear non-competitive in cost terms. It is argued that competition has been fierce in the past decades with many large, multi-national car manufacturers struggling to survive (Dijk *et al.*, this Section). Such companies have found it both more attractive and safer to invest in innovation in the existing IC engine technology than in technological options that carry the risk of low consumer acceptance. This yields a pattern in which car manufacturers continuously refine the dominant design in order to improve environmental performance of IC engines (Dijk and Yarime, 2010), rather than making a ‘great leap forward’. Thus, the development of hybrid technology can be seen as an attempt by car assemblers to innovate without having to move away from their core competencies. On the infrastructure side, the ‘refuelling’ sub-system includes storage at the filling station and the refuelling process itself. Here liquid biofuels hold out the prospect of retaining the existing transport infrastructure (e.g., refuelling or ‘petrol’ stations), in contrast to other low carbon options, such as EVs and hydrogen-fuelled vehicles (Hammond *et al.*, 2012).

The last five years (i.e., 2005–2010) has been a greater period of innovation in electric mobility. The central thesis of Dijk *et al.* (this Section) is that this electric mobility has crossed a critical threshold and is now benefitting from various developments whose influence can be expected to grow in importance: high oil prices, carbon constraints, and the rise of organised car sharing and inter-modality. Dijk *et al.* find that the development of vehicle engine technology is dependent on alterations in mobility preferences, changes in the global car market, reshaping of the refuelling infrastructure, fluctuations in energy prices, adjustments in climate policy, and structural developments in the electricity sector. The co-authors consider the potential consequences of the interaction of technological alternatives, including future synergies between battery PiV, hybrid electric, and hydrogen fuel cell vehicles. These are likely to be important drivers for the future evolution of the interlinked energy and transport sectors out to 2050 and beyond.

7. Branching Points and Some Next Steps

The transition pathways developed by the consortium have recently been enhanced by the development of ‘branching points’ - points at which decisions may be taken to diverge from the existing trajectory, towards another pathway or a hybrid, or to return to a pathway after deviating from it. Branching points may be negative (e.g., the failure of a low carbon technology to come on stream as expected) or, more fundamentally, a loss of faith in the prevailing logic, such as a move away from the market towards greater central co-ordination or local action. In contrast, they may be positive, as in unexpectedly successful developments in technology or infrastructure. The paper by Foxon *et al.* (this Section) describes initial analysis of branching points from the three low carbon, more electric transition pathways.

They explore and analyse branching points identified through project and stakeholder workshops, and drawing on an analysis of actors' choices and responses at past branching points in energy system transitions (Arapostathis *et al.*, this Section). The potential responses of the actors are identified at these branching points, and risk mitigation strategies (see also Hammond and Waldron, 2008) are formulated for the dominant actors to reinforce that pathway, as well as opportunities for actors to move away from the pathway. Understanding the pressures, tensions and processes that lead to branching points, it is suggested by Foxon *et al.* (this Section), means being better able to anticipate, address – or even precipitate – them.

In May 2012 a follow-on research project was initiated with funding from the EPSRC entitled '*Realising Transition Pathways: Whole Systems Analysis for a UK More Electric Low Carbon Energy Future*' (under Grant EP/K005316/1). It involves the same nine academic partner institutions, and will seek to explore the constraints and opportunities in realising a low carbon UK energy sector, including those stemming from European developments. This new research project will include studies on the horizon scanning of innovative energy technologies over the period to 2050, the feasibility of demand responses (after Barton *et al.*, this Section), uncertainties in economic analysis, the estimation of investment costs of the different pathways, and the implications of markets for investment decisions about energy technologies. Further work will be undertaken on conceptualising, mapping and analysing 'actor dynamics' in the contemporary UK electricity sector (after Hargreaves *et al.*, this Section), historical transitions and case studies (after Arapostathis *et al.*, this Section), integrated energy networks modelling and evaluation [after Barnacle *et al.* (this Section) and Pudjianto *et al.* (this Section)], and 'whole systems' energy and environmental appraisal of low carbon technologies and pathways (after Hammond *et al.*, this Section). The consortium also intends to continue the development of their initial work on the branching points approach described above (Foxon *et al.*, Arapostathis *et al.*, this Section), and to identify and explore other potential branching points on the core transition pathways. In addition, the '*Realising Transition Pathways*' project will seek to identify and examine other past branching points, in search of patterns, insights and typologies that might inform understanding of, and agency in relation to, prospective branching points on the transition pathways to a low carbon, more electric future for the UK.

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perspectives on socio-technical issues concerning the implementation of smart grids and the take-up of electric vehicles respectively. The Guest Editors are grateful to the reviewers for the time and diligence they spent in evaluating the papers brought together here. Likewise, the *Transition Pathways* (TP) project has benefited over time from the help and advice of John Bateman, Andy Boston, Mike Garwood, and Stephen Plimmer of *E.On UK* and of Neil Bateman, David Holtum, and Jacqui Williams from the EPSRC. In addition, the TP Advisory Board was ably and insightfully chaired by James Smith (formerly the Chairman of *Shell UK* and now Chairman of the *Carbon Trust* in the UK), and consisted of Tera Allas [Director General for Strategy, Analysis and Better Regulation at the *Department for Business, Innovation & Skills (BIS)* and Deputy Head of the UK *Government Economic Service*], Jenny Cooper (R&D Specialist at *National Grid*), David Joffe (Senior Analyst at the independent *Committee on Climate Change*), René Kemp (Professor of Innovation and Sustainable Development at Maastricht University, the Netherlands), Jan Ole Kiso [Senior Policy Advisor with the Strategy Unit at the *Department of Energy and Climate Change (DECC)*], Adam Morton (Chief of Low Carbon Technology at *Rolls Royce plc*), Sarah Samuel [Head of Sustainable Energy Policy at the *Office of Gas and Electricity Markets (Ofgem)* – the market regulator], and Garry Staunton (principal of *Staunton Associates*), as well as representatives from both *E.On UK* and the EPSRC. However, the views expressed here are those of the authors alone, and do not necessarily reflect the views of the collaborators or the policies of the funding bodies. Finally, the Guest Editors are very grateful for the support of Miles Davis (University of Bath) as the TP Project Manager, along with his colleagues Lacey-Jane Davis and Carolina Salter.

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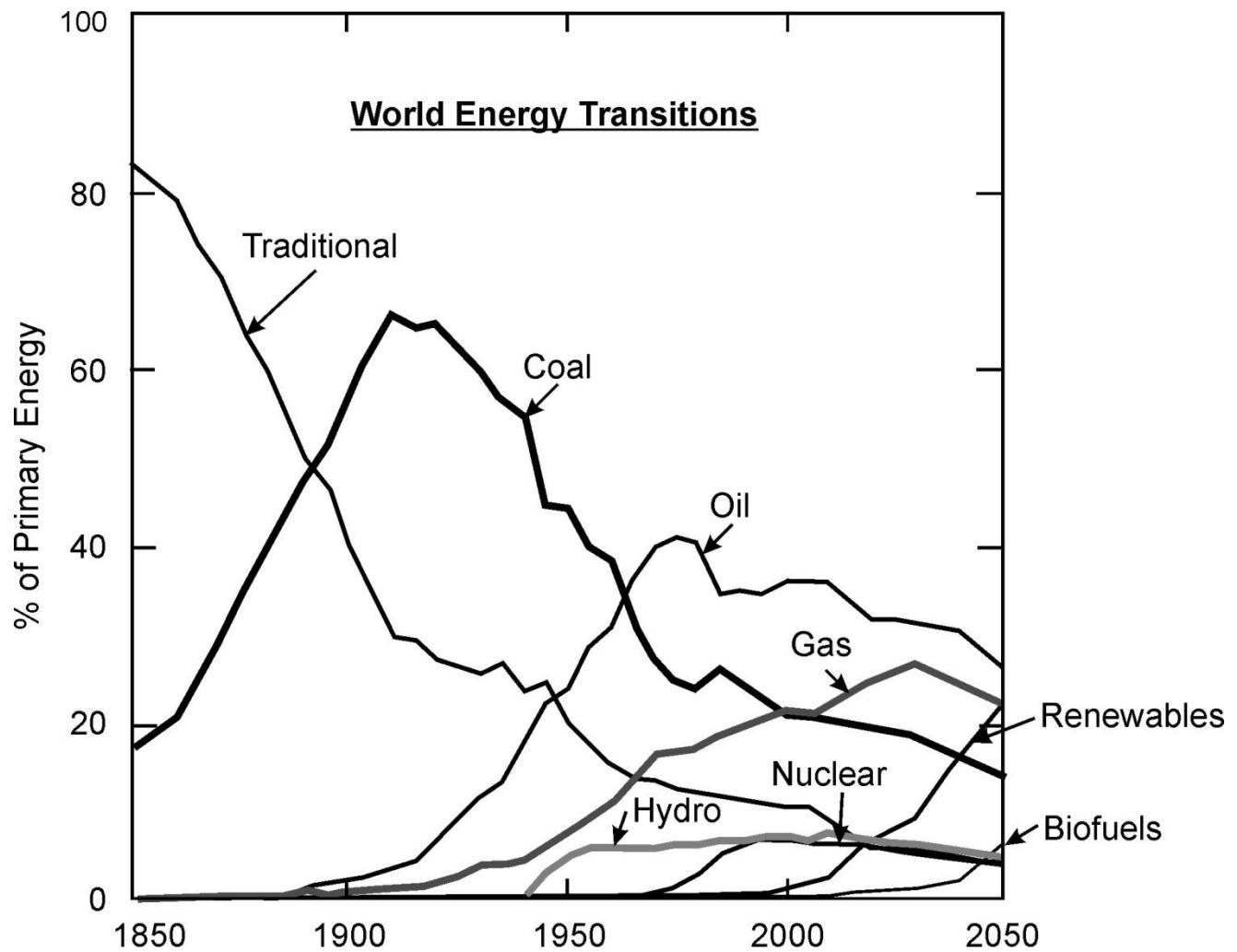


Fig. 1 World primary energy shares 1850-2050: future projections based on the Shell ‘*Dynamics as Usual*’ Scenario. [Source: Hammond and Waldron, 2008; concatenated from the data in Nakicenovic *et al.*, 1998 and Shell projections reported by Davis, 2001].

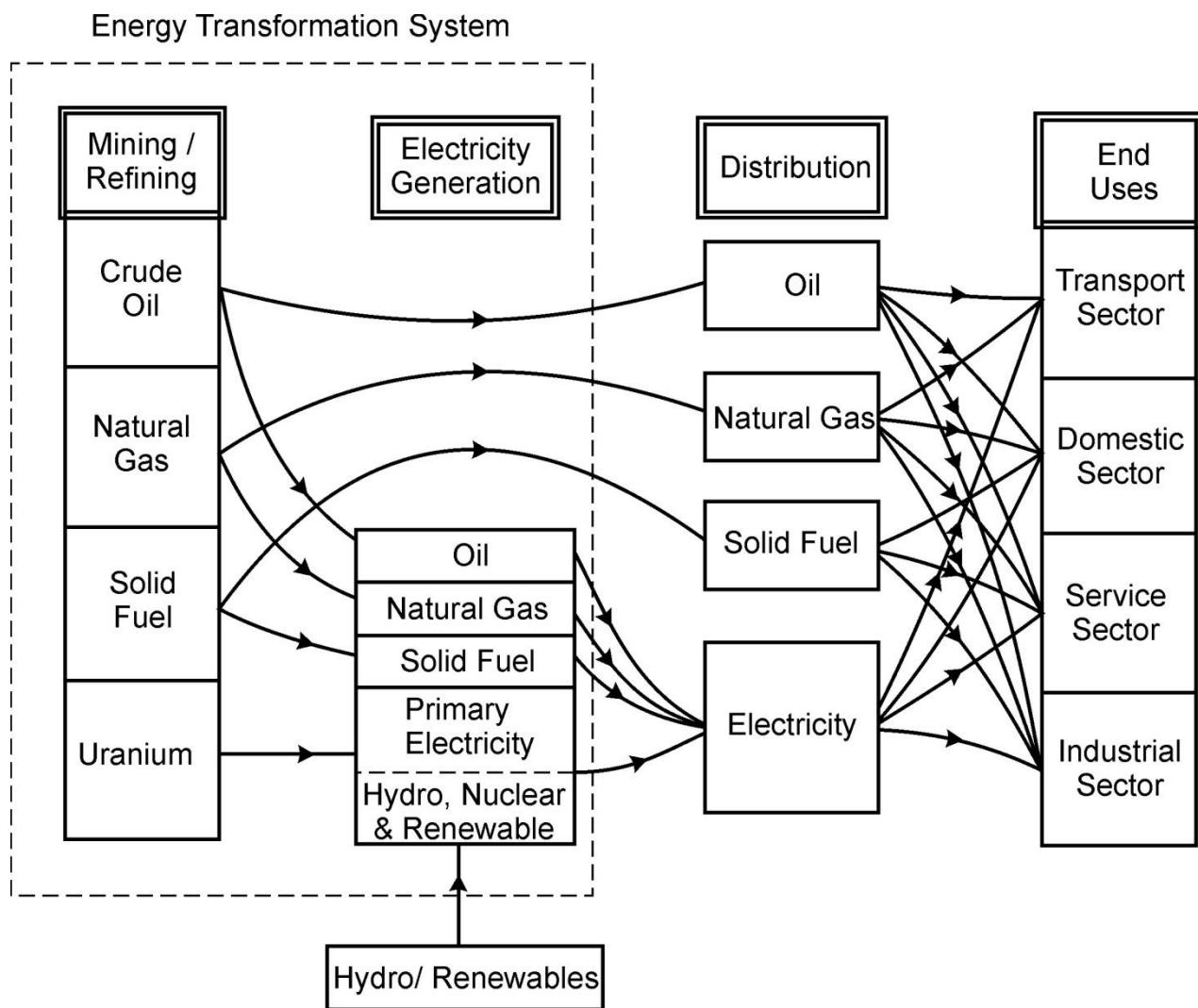


Fig. 2. A simplified representation of the UK energy system. [Source: Hammond, 2000].

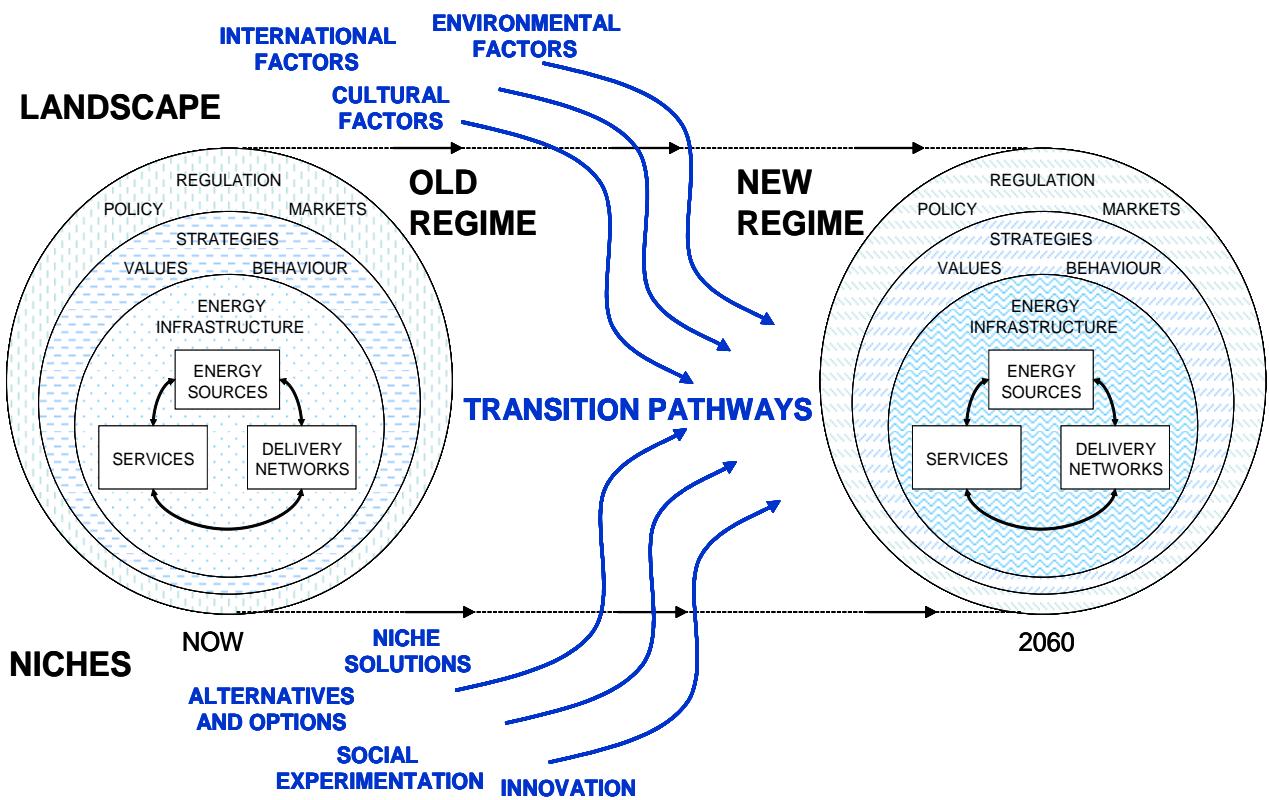


Fig. 3. Possible transition pathways and the factors that influence them. [Source: The Transition Pathways Consortium (Foxon *et al.*, 2010)].