Transition pathways for a low carbon energy system in the UK: assessing the compatibility of large-scale and small-scale options

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Abstract

This paper describes initial work on transition pathways for a low carbon energy system in the UK, being pursued in a major new research project. The project is a collaboration between leading UK engineers, social scientists and policy analysts, supported by the UK Engineering and Physical Sciences Research Council (EPSRC) and the energy company E.ON UK. The project aims to (a) to learn from past transitions to help explore future transitions and what might enable or avoid them; (b) to design and evaluate transition pathways towards alternative socio-technical energy systems and infrastructures for a low carbon future; and (c) to understand and where appropriate model the changing roles, influences and opportunities of large and small 'actors' in the dynamics of transitions. The paper describes the development of outline transition pathways and the approach to assessing these through electricity network modelling and participatory interviews with stakeholders and end-users. Pathways being investigated include (1) those focussing on large-scale centralised low-carbon supply-side options, with greater roles for any or all of renewables, nuclear and fossil fuels with carbon capture and storage; and (2) those with greater take-up of demand-side options, involving both active demand side management through load shifting and reduction as well as electricity generation at point of use. The paper focuses on how these pathways are being used to assess the extent to which the large-scale and small-scale pathways are compatible, or whether choices need to be made by UK energy policymakers and stakeholders as to which pathway is preferable.

1. Introduction

This paper describes initial work on transition pathways for a low carbon energy system in the UK, being pursued in a major new research project. The project[1] is a collaboration between leading UK engineers, social scientists and policy analysts, supported by the UK Engineering and Physical Sciences Research Council (EPSRC) and the energy company E.ON UK.

The project will undertake historically-informed and forward-looking analysis of energy system transitions, bringing together quantitative and qualitative research methods, to address three research challenges:

- To learn from past transitions to help explore future transitions and what might enable or avoid them;
- To design and evaluate transition pathways towards alternative socio-technical energy systems and infrastructures for a low carbon future; and
- To understand and where appropriate model the changing roles, influences and opportunities of large and small 'actors' in the dynamics of energy transitions.

The overall research aims are:

- to select, develop and analyse a set of potential transition pathways for the UK energy system to a low carbon future, and
- to undertake integrated assessments of the technical and economic feasibility and social and environmental potential and acceptability of these pathways.

This paper describes the development of outline transition pathways, a process that builds on a conceptual and analytical framework based on the literature on transitions in socio-technical systems, on a review of UK energy scenarios and on interviews with key 'gatekeepers' in the UK energy industry and policy communities. We are investigating pathways that include (1) those focussing on large-scale centralised low-carbon supply-side options, with greater roles for any or all of renewables, nuclear and fossil fuels with carbon capture and storage; and (2) those with greater take-up of demand-side options, involving both active demand side management through load shifting and reduction as well as electricity generation at point of use. The elucidation of these pathways will embrace the evolution of the physical and institutional infrastructure changes, and the roles of actors, both large, e.g. multinational energy supply and distribution companies, national governments, major investors, and small, e.g. households, innovators and entrepreneurs. This paper focuses on how these pathways are being used to assess the extent to which the large-scale and small-scale pathways are compatible, or whether choices need to be made by UK energy policymakers and stakeholders as to which pathway is preferable.

Section 2 of the paper summarises the main theoretical approaches that the project draws on. Section 3 briefly describes the approach being taken to developing and analysing transition pathways, combining elements of the three theoretical approaches. Section 4 describes the initial work on developing outline transition pathways for UK energy systems. Section 5 discusses some key issues raised by

[1] The project 'Transition pathways to a low carbon economy' involves Universities of Bath, Loughborough, Strathclyde, Surrey, East Anglia, Leeds, Imperial College and King's College London, runs from May 2008 to October 2011, and is funded by EPSRC and E.ON UK, under grant ref.: EP/F022832/1.

examining the consistency and compatibility or tension between these pathways, that will be further investigated in the project.

2. Theoretical approaches

The conceptual framework for the project draws on and integrates three existing and developing bodies of research – on *long-term socio-technical transitions*, *technological innovation systems*, and *co-evolutionary dynamics*.

2.1. Socio-technical transitions research

Dutch researchers have pioneered an ongoing research programme on *transitions in socio-technical systems,* that has generated significant international attention and interest (Elzen et al., 2004a; Geels, 2005a). This approach draws on earlier work on technology and innovation studies, evolutionary economics, sociology and institutional theory.

This transitions research combines technical, social and historical analysis of and insights into past and current transitions, using an analytical framework based on interactions between three 'levels': *technological niches*, *socio-technical regimes*, and *landscapes* (Kemp, 1994; Geels, 2002). The *landscape* (macro) level represents the broader political, social and cultural values and institutions that form the deep structural relationships of a society and only change slowly. The *socio-technical regime* (meso level) reflects the prevailing set of routines or practices used by actors, which that create and reinforce a particular technological system, including "engineering practices; production process technologies; product characteristics, skills and procedures […] all of them embedded in institutions and infrastructures" (Rip and Kemp, 1998). Whereas the existing regime generates incremental innovation, radical innovations are generated in micro-level *niches*, which are spaces that are at least partially insulated from 'normal' market selection in the regime, for example, specialised sectors or market locations. Niches provide places for learning processes to occur, and space to build up the social networks that support innovations, such as supply chains and user-producer relationships. Transition pathways arise through the dynamic interaction of technological and social factors at these different levels.

Research under the transitions approach has developed along two main lines. Firstly, the multi-level perspective is used as a framework within which *the historical dynamics of transitions* may be analysed. Verbong and Geels (2005) analysed the historical dynamics within the Dutch electricity system from 1960 to 2004. Other analyses have examined transitions from sailing ships to steam ships (Geels, 2002); from horse-drawn to automobile transport systems (Geels, 2005b); from cesspools to sewer systems (Geels, 2006); and biogas development in Denmark (Geels and Raven, 2007). Secondly, the transitions approach has been used as a basis for developing 'transition management'. This is a process of governance seeking to steer or modulate the dynamics of transitions through interactive, iterative processes between networks of stakeholders. It involves creating shared visions and goals, mobilizing change through transition experiments, and learning and evaluation of the relative success of these experiments (Kemp and Rotmans, 2005; Loorbach, 2007). Transition management is thus a form of participatory policy-making based on complex systems thinking.

In our work, we seek to understand and contribute to potential future transitions of UK energy systems. In order to do this, we combine elements of historical analysis, which inform how the broad, long-term sweep of dynamics arises out of interactions between actors, institutions and infrastructures, i.e. a multi-level perspective, with elements from transition management, which show how purposeful actions by actors within systems can give rise to changes in institutions and infrastructures. The multi-level perspective has also been used as the basis for developing *socio-technical scenarios*, which seek to explore the potential future development of socio-technical systems through interactions between ongoing processes at the three levels (Elzen et al., 2002; Elzen et al., 2004b). The transition pathways framework developed in this project is an elaboration of the socio-technical scenarios approach, augmented by recent thinking in two other bodies of research, described in the following sections.

2.2. Technological Innovation Systems

Whilst the transitions approach seeks to understand long-term changes to socio-technical systems by analysing interactions between technological and social elements, a complementary research strand focuses on a more detailed understanding of innovation processes from a systems perspective. This research examines the feedback mechanisms and interactive relations involved in the development and application of new knowledge. These interactions involve science, technology, learning, production, policy and demand, so that firms and entrepreneurs innovate largely in response to incentives coming from the wider innovation system. The approach emphasises the importance of non-linearity, as new technologies typically show increasing returns to adoption, so that small changes in initial conditions can result in radically different outcomes.

Recent research has focused on analysing *technological innovation systems*. Carlsson and Stankiewicz (1991) define these as "networks of actors interacting in a specific technology area under a particular institutional infrastructure for the purpose of generating, diffusing, and utilizing technology". Hence, a technological innovation system is made up of three main elements:

- *Actors*, including technology developers, users, policy-makers and regulators. These actors have limited ability to gather and process information for decision making – so-called 'bounded rationality', but have particular capabilities or competences which they can employ.
- *Networks* through which actors share knowledge and exchange information. These include formal interactions, e.g. through exchange within markets, but also informal interactions, e.g. through trade associations.
- *Institutions* which stipulate the norms and rules for interactions between actors, and so influence the rate and direction of innovation.

Because the future is uncertain and firms lack perfect knowledge, what they know and how they learn becomes central to understanding the innovation process. Much innovation consists of making new combinations of existing knowledge, as a result of various forms of learning: *learning-by-doing* (Arrow, 1962); *learning-by-using* (Rosenberg, 1982) and *learning-by-interacting* (Lundvall, 1993). Furthermore, the uncertain nature of innovation implies that firms' and investors' *expectations* of future markets, technologies and policies are a crucial influence on their decisions about which technologies to invest in and develop (MacKenzie, 1992). Expectations are often implicitly or explicitly shared between different firms in the same industry, giving rise to trajectories of technological development which resemble self-fulfilling prophecies.

2.3 Co-evolutionary approaches

A third body of research has used a co-evolutionary approach to long-term processes of stability and change, in which dynamics are determined by causal influences between mutually evolving systems. Freeman and Louca (2001) seek to explain long-term changes in techno-economic systems through the interactions between five evolving systems relating to science, technology, economics, politics and culture. A process of technological and institutional co-evolution, driven by path-dependent increasing returns to scale, has been used to explain the state of '*carbon lock-in*' to modern carbon-based energy systems, preventing the development and take-up of alternative low-carbon technologies (Unruh, 2000; Foxon, 2007).

Recent research in this area has developed an analytical framework to analyse ongoing, iterative dynamics involving technologies, institutions, and business strategies. A process of co-evolutionary interactions between technological development, institutional change and business strategies has been used to analyse the relative success of firms in different European countries in the 19th/20th Century development of the synthetic dye industry (Murmann, 2003); to analyse the role of incumbent utilities in the recent take-up of renewable energy technologies in different European countries (Stenxel and Frenzel, 2007; Stenzel et al., 2008); and to analyse of the role of sustainability-driven entrepreneurs in the take-up of renewable energy technologies in the U.S. (Parrish and Foxon, 2008). Co-evolution is defined here as "two evolving populations coevolve if and only if they both have a significant causal impact on each other's ability to persist" (Murman, 2003, p.210). This causal influence can arise through two avenues: by altering selection criteria or by changing the replicative capacity of individual entities. Nelson (1994, 2005) has applied analysis of the co-evolution of technologies, industrial structures and institutions to understanding innovation systems and economic growth. Building on this work, Beinhocker (2005) argues that these co-evolutionary interactions have driven the creation of wealth in Western industrialised countries, crucially through the development of property-right based market economies which encourage the innovation of physical and social technologies for more efficiently and effectively meeting (and creating) consumer demands.

3. Approach to developing and analysing transition pathways

The overall project 'Transition Pathways to a Low Carbon Economy' consists of three themes, each involving two or three workstreams. Theme 1 consists of workstreams on transitions, scenarios and historical analysis. Theme 2 is undertaking technical and social analysis of supply-side, demand-side and infrastructure networks, through workstreams on participation, sources and infrastructure. Theme 3 consists of workstreams on whole systems analysis, and on joint working, integration and learning. The development of transition pathways under Theme 1 will both draw on and contribute to work under the other themes and workstreams. The formulation of transition pathways will focus on processes relating to the co-evolution of technologies, institutions, business strategies and, also, user practices. These processes arise through interactions between activities at the niche, regime and landscape levels. We will particularly focus on examining innovation systems for new technologies at the niche level as they challenge the dominant regime.

The formulation of transition pathways follows an approach based on three elements:

(1) *Characterise existing energy regime and pressures on it*;
(2) *Identify dynamic processes at the niche level*; and
(3) *Specify interactions giving rise to transition pathways*.

The relation between these elements is illustrated in Figure 1.

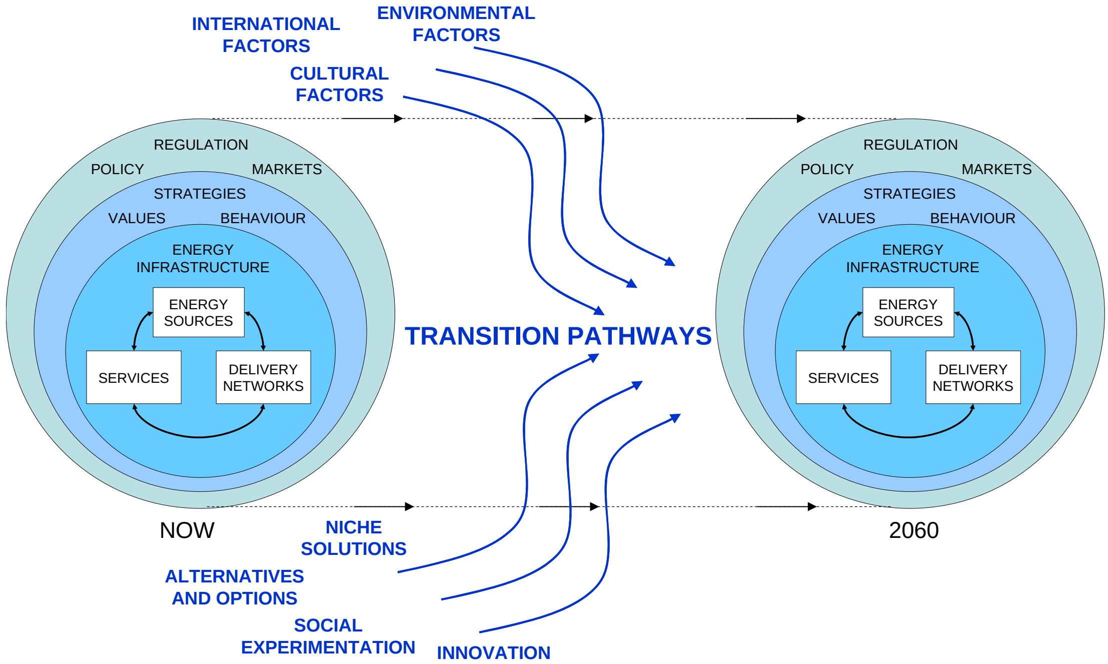

***Figure 1**: Possible Transition Pathways and the Factors that Influence them*

The initial application of this framework to the development of transition pathways to a low carbon energy system for the UK is described in Section 4.

3.1. Stages and Key activities

The research will be structured around the three overall project stages, facilitating interactions between workstreams. Key tasks for each stage are:

Stage 1: Development of Frameworks and Outline Pathways

Stage 1 involves the development of a conceptual and analytical framework and the specification of outline transition pathways. This work will draw on activities within other workstreams and interactions with stakeholders, including a review of existing scenarios for the development of UK energy systems. This will help to elucidate key insights from these scenarios, but also current weaknesses in forecasting the *evolution* of a low carbon economy. It will highlight issues raised for the assessment of the feasibility of these scenarios in terms of engineering, institutional, social processes, required policy interventions, and international assumptions. Under the participation workstream, semi-structured interviews are being undertaken with key ‘gatekeepers’ (individuals and organisations) to ascertain their understanding of the different knowledge and practice networks that constitute the existing energy regime in the UK. A workshop will then be held in November 2008 with a range of external stakeholders from industry, academic and policy-making communities to review the draft transition pathways to ensure their relevance and consistency.

Stage 2: Explore and Interrogate Pathways
Stage 2 involves the exploration and interrogation of these pathways using technical and social assessment. It will also draw on lessons from the study of historical pathways. This will involve quantitative and qualitative assessment of sustainable generation and infrastructure developments and the possibilities for and implications of supply-side participation (through network interactions) and demand-side participation (both automated and that requiring human intervention) and distributed generation.

Stage 3: Complete Pathway Exploration; Produce, Test and Deliver Findings
Stage 3 involves the completion of pathway exploration and production, testing and delivery of overall research findings. The findings of the technical and social assessments will be brought together through the application of a 'toolbox' of whole systems assessment techniques, and the elucidation of detailed transition pathways. They will be refined through a process of communication and engagement with stakeholders, in order to disseminate both detailed findings and overall insights that have emerged from the research, particularly for industry and policy stakeholders. It is envisioned that the final transition pathways will focus on three 15-year periods, covering 2008-2022, 2023-2037 and 2038-2052 which correspond to the 5 year carbon budgeting periods proposed in the draft Climate Change Bill.

4. Developing outline transition pathways for UK energy systems

The initial development of the outline transition pathways for UK energy systems described here, will be augmented by the findings from the review of UK energy scenarios and the interviews with key 'gatekeepers'. The pathways will then be assessed and reviewed at the stakeholder workshop.

4.1. Characterise existing energy regime and pressures on it
The current UK regime for meeting lighting, heating and power-related services may be characterized as a centralized system. Electricity is generated centrally, largely from natural gas, coal, nuclear power and a small but growing set of renewable sources, and delivered to homes and businesses through the transmission and distribution networks, before being used to provide lighting, heating and power services with the aid of end-use technologies and the buildings infrastructure. Similarly, natural gas, produced from the North Sea or imported via pipelines or as liquefied natural gas (LNG), is delivered through the distribution network, and used mainly to provide heating and cooking services with the aid of end-use technologies and the buildings infrastructure. The markets for the provision of electricity and gas were liberalized in the 1990s to facilitate competition between electricity generators, and between companies supplying electricity and gas to homes and businesses, overseen by a regulator Ofgem. The strategic importance of energy to enabling well-being and economic activity means that the system is the subject of intense policy activity, focussed on ensuring continuing, affordable supplies, and meeting other social and environmental objectives.

Key processes at the landscape level influencing and 'driving' the energy regime include:

- public awareness of climate change and willingness to accept and undertake changes in response;
- government commitments to meet national and international targets for emissions reductions and promotion of low carbon energy sources;
- ideological commitments to liberalized energy markets;
- concerns over security of primary energy supplies;
- external factors leading to high oil and gas prices; and
- factors which could lead to physical disruption of external supplies (war, terrorism, foreign governments limiting supply, etc.).

The dominant processes at present (2008) are governmental commitment to national and international targets for moving to a low carbon energy system and concerns over security of supply, with growing concerns over affordability and fuel poverty. In the draft Climate Change Bill currently before Parliament, the UK government has committed itself to achieving at least a 60% reduction in CO_2 emissions by 2050, with an interim target of a 26-32% reduction by 2020. The 60% target was first formally made in the 2003 Energy White Paper, but without any strong supporting institutional structure to ensure a pathway to this target was followed (Foxon and Pearson, 2007). The government is enacting the Climate Change Bill to make this target legally-binding, driven by the increasingly disturbing scientific predictions, the rapidly increasing public awareness of the issue and the analysis provided by the Treasury's Stern Review (Stern, 2007), which argued that the economic costs of action to mitigate climate change were likely to be significantly lower than the costs and risks associated with the impacts of climate change. The institutional innovations of legally-binding targets and a strong Climate Change Committee will enable the government to be held to account, so that much stronger pressures on the energy regime will result.

In addition, the UK has signed up to, and was one of the drivers of, the European energy and climate policy, agreed at the Council of Ministers in 2007. This sets targets for 2020 of a 20% reduction in European CO_2 emissions, a 20% increase in energy efficiency and 20% of final energy to come from renewable sources. The European Commission's proposal for how this latter target is to be shared out between countries envisions a target of 15% of final energy from renewable sources for the UK. How the UK will achieve this target is now the subject of a UK government consultation (BERR, 2008b). The target will be very challenging, as UK renewables policy has largely focused on electricity generation, with little attention to renewable heat or transport sources until very recently. It has been speculated that this would mean a target of 30-40% of renewably generated electricity by 2020. This compares to the current goal of 20% renewable generation by 2020, with currently only firm incentives through the Renewables Obligation to achieve 15% by 2015. Hence, the landscape-level commitments contained in the National and European energy and climate policy targets will need to be translated into direct pressures on the energy regime through enhanced policies and measures.

The second main driver of UK energy policy at the landscape level is concerns over security of primary energy supplies. A variety of factors between now and 2020 have led to a perceived generation 'gap' and concerns about availability of primary energy sources to enable this gap to be filled whilst achieving carbon reduction targets. These influences include high oil and gas prices, more rapid decline of UK North Sea oil and gas production than expected, concerns about dependence on imported gas from Russia and the Middle East, and a growing awareness that by 2016-2020 most of the current and ageing nuclear generating capacity will close, as will some coal-fired power stations that do not meet the requirements of the Large Combustion Plant Directive. This has led to pressures on the energy regime, in the form of support in principle for the building of new nuclear power stations (BERR, 2008a) and consent for new coal-fired power stations. These policies have also been strongly driven by lobbying from actors within the existing regime seeking to maintain the current centralized generation system and their role in it.

Other strong drivers within the existing regime are increases in electricity and gas prices for households and industry, resulting from increases in international oil and gas prices – and associated growing concerns over energy affordability and fuel poverty, and changes in users' responsiveness to higher prices; and increasing concerns over climate change, which could translate into growing willingness to accept and undertake change in response. At the moment, both governments and large energy industry players seem to believe that most users are still more driven by a desire for stable energy supplies at the lowest possible cost, rather than by responses to climate change concerns.

An interesting potential institutional innovation is a proposal to encourage the selling of energy *services* rather than units of energy from 2012, under the government's Carbon Emission Reduction Target scheme, which requires energy suppliers to stimulate take-up of low carbon and energy efficient measures by their customers. This could potentially lead to significant changes in business strategies for large industry players, particularly if they face challenges from new entrepreneurial energy service companies.

How these different pressures affect business strategies depends partly on how firms perceive the various risks within the system. A survey of a range of stakeholders identified the major risks associated with a rapidly changing UK electricity sector as being: reliance on insecure sources of primary fuels for electricity generation; lack of investment in new infrastructure; decommissioning of nuclear plant leading to reduced capacity; severe weather conditions arising from climate change; and maintenance of capacity margins (Hammond and Waldron, 2008).

At the same time, the existing regime has acquired a (social) stability and inertia through the investments in existing technologies, infrastructures and institutions, so that most change is incremental and relatively slow. Thus, the rate of capital turnover, the amount of new infrastructure needed and the rate of institutional change provide key factors that influence the extent to which the existing regime will be destabilized.

4.2. Identify dynamic processes at the niche level

Developments are ongoing at the niche level through the formation of technology-specific innovation systems around a number of different technological alternatives. A technological innovation system may encompass one or more technological/ market niches (Markard and Truffer, 2008). Alternatives include both centralized options, such as offshore wind, wave and tidal power, tidal barrages, biomass co-firing, new nuclear power, and carbon capture and storage (CCS), and decentralized options, such as combined heat and power (CHP) through gas-powered fuel cells or Stirling Engines, local energy crops, photovoltaics, micro wind generation, solar heating and ground-source heat pumps. A key task for the development of the outline transition pathways is the elucidation of potential virtuous cycles between the different processes or functions which could occur within each of these technological innovation systems.

These innovation systems may be seen as competing for resources and recognition against each other within the centralized or decentralized paradigm, at the same time as these two paradigms compete against each other. Of course, complementarities may also exist between different technological alternatives, both within and between paradigms.

4.3. Specify interactions giving rise to transition pathways

It is useful to impose a broad structure to clearly differentiate transition pathways. Firstly, we take as given the need to achieve a transition in UK energy systems to contribute to at least a 60% reduction in CO_2 emissions by 2050, compared to 1990 levels. This will become a legally-binding target on the UK Government if, as expected, the Climate Change Bill currently being considered by Parliament is enacted. The Government has also formed a new institution, the Climate Change Committee consisting of external energy and climate experts, to recommend five-year carbon budget periods towards the target and to advise it on whether the 2050 target should be strengthened to a 80% reduction target (Defra, 2007). Whilst making a target legally-binding does not guarantee its achievement (and the Bill allows for the buying in of carbon credits relating to overseas emissions reductions), we assume that the strengthening scientific basis for human-induced climate change and its impacts (IPCC, 2007), as well as the economic case for urgent action advanced in the Stern Review (Stern, 2007), will result in a domestic emissions reduction target of the order of 60-80% being agreed sooner or later by the UK, as it seeks to show leadership in international negotiations.

Of course, human contributions to climate change are determined by cumulative emissions and concentrations and not by arbitrary end-points (Anderson and Bows, 2007). Hence, we take one dimension of our structure to relate to early or late strong action to put the UK on a path to achieve a 60-80% reduction in CO_2 emissions by 2050. We take early actions to mean actions to achieve a domestic 30-40% emissions reduction by 2020. Because of the long lead times for much capital and infrastructure investment, this will require significant actions to be taken in the three carbon budgeting periods 2008-2012, 2013-2017 and 2017-2022.

The second dimension is that of moves towards largely centralized or largely decentralized electricity systems. Whilst many different alternatives exist within each of these routes, they are significantly different from each other, particularly in terms of infrastructures, institutions and patterns of behaviour. Together with the early/late action dimension, this will enable investigation of the extent to which it is feasible and efficient to maintain both largely centralized and largely decentralized options, or whether going down one pathway would preclude going down the other.

The interactions of the ongoing dynamic processes at landscape, regime and niche levels will be used to formulate transition pathways in UK energy systems. These pathways will be specified through what will be judged to be mutually consistent processes at the different levels coming together in virtuous circles of cumulative causation. These judgments will be based on initial interactions with public and private stakeholders, through the interviews and stakeholder workshop taking place in the early stages of the project. Here, we sketch out some early thinking about how potential transition pathways could be formulated, although subsequent analysis could lead to significant changes as the project develops.

(1) *Later-action/centralized generation systems*: In this pathway, concerns over security of supply, and doubts about the potential to scale up local decentralized technologies, reinforce strategies of large energy companies to maintain portfolios of large-scale technologies, including coal and nuclear power. Hence, investment focuses on these technologies, alongside scale-up of offshore wind, and reinforcement and enhancement of existing transmission infrastructure. The way that targets for emissions reductions and renewable energy sourcing are institutionalized allows investment by UK companies overseas to count towards UK targets, and so UK domestic targets are less stringent, delaying early action on decentralized options, and reducing the overall pace of change.

(2) *Later-action/decentralized generation systems*: In this pathway, technical, social and economic concerns relating to the main centralized options, including carbon capture and storage, nuclear power and offshore wind, lead to a renewal of interest in decentralized options in the period 2016-2020, as the existing regime is seen to be struggling to meet climate change and energy security goals. However, lack of investment has delayed the development of these options, and multiple decentralized options now compete. Lack of co-ordination between these options, together with stranded assets from earlier centralized investments, slows down necessary investment in distribution networks.

(3) *Early-action/centralized generation systems*: In this pathway, key centralized generation technologies, including nuclear power and larger-scale offshore wind, are given strong institutional support, e.g. by over-riding local planning objections and investment in relevant skills and training. Growing public acceptance of the need for action on climate change and energy security reinforces these developments and the need for domestic UK action, and company strategies focus on developing known existing technologies rather than more risky options. This investment in centralized technologies, and associated infrastructure, crowds out the potential for large investments in decentralized options.

(4) *Early-action/decentralized generation systems*: In this pathway, a strong commitment to domestic action by government and companies creates positive expectations which guide search activities towards decentralized options. Strong local leadership and sharing of knowledge between entrepreneurial local authorities is reinforced by advocacy coalitions of technology developers, installers and new energy service companies

promoting decentralized generation. Infrastructure investment is focused on enhancing capacity of distribution networks to actively manage two-way power flows and on investment in the built infrastructure to capture natural energy flows, e.g. through passive solar design and natural ventilation.

5. Discussion

The starting point for this work is that a transition to a radically different energy system is needed to meet the twin challenges of decarbonisation to mitigate climate change and ensuring security of energy supply. Lesson from the study of past systems transitions show them to be complex, involving many actors interacting within institutional structures, under conditions of risk and uncertainty, so that outcomes can not be predicted. Nevertheless, these studies show some common patterns within transitions, including the inertia and entrenchment of the existing system in response to pressures; these pressures are both top-down from broader social and cultural changes, and bottom-up from technological and social innovation within expanding niches. We argue that exploring these patterns within potential future transition pathways can be useful to interested stakeholders, including policy-makers, businesses and other actors. This goes beyond existing scenario approaches by exploring in more detail the interactions by which future end states may arise.

Clearly, this is a crucial time in the development of UK energy systems, in general, and electricity systems, in particular. Extrapolations of future demand and expectations of the retirement of many current nuclear power stations, as they reach the end of their lives, and the closure of some coal-fired power stations by 2016, under the EU Large Combustion Plant Directive, have led to predictions of a supply 'gap' within the next decade. Large energy system players have responded by successfully lobbying for government support for building of new nuclear power stations, and in planning to build new coal-fired power stations, designed to be 'ready' for the later addition of carbon capture and storage technologies. At the same time, both larger and smaller players are investing in innovation of a range of low carbon energy technologies. Analysis of technological innovation systems suggests that if these technologies are to challenge the dominance of the existing energy regime, then 'virtuous cycles' of positive feedbacks between different functions or processes within these systems need to be generated (Jacobsson and Bergek 2004; Hekkert et al., 2007). These processes include not only the development and diffusion of new knowledge, the stimulation of entrepreneurial activities, and the creation of markets for these options, but also the management of expectations of future potential and the creation of 'legitimacy', through the development of the necessary supporting rules, skill sets and public acceptability of new options. These processes are supported by the ways in which the broader social and cultural pressures are articulated to guide the activities of entrepreneurs and innovators.

As noted, there are two main ways in which the UK government is currently seeking to articulate the broader pressure for mitigating climate change. Firstly, through the setting of legally binding targets for carbon reduction of at least 60% by 2050 and at least 26% by 2020, and the requirement for the Climate Change Committee to advise on how these targets could be achieved, in five year commitment periods. These recommendations may challenge the government to realize greater coherence in its mix of policies to achieve these targets. Secondly, through the proposed strategy for the UK to meet its target, under the EU agreement, of 15% of final energy from renewables by 2020, which is currently out for consultation (BERR 2008b). Proposed measures include:

- extending and raising the level of the Renewables Obligation to encourage up to 30-35% of UK's electricity to come from renewable sources by 2020;
- introducing a new financial incentive mechanism to encourage a very large increase in renewable heat; and
- ensuring appropriate incentives for new electricity grid infrastructure and removing grid access as a barrier to renewable deployment.

The illustrative renewable technology breakdown, shown in the BERR consultation document, envisages a large range of technologies contributing to reaching the 2020 target. Interestingly, large scale technologies dominate the renewable electricity options, with the biggest contributions to the target coming from offshore wind (19% contribution) and onshore wind (13%), and less than 1% coming from microgeneration electricity. On the other hand, the renewable heat options are dominated by smaller scale technologies, including the use of biomass in local combined heat and power (CHP) schemes (15%), and solar heating (9%). Conventional modelling assumes that these technologies will be adopted when they become cost-competitive with other options under the relevant support schemes, provided that well-known barriers to adoption are overcome, such as the difference in incentives facing landlords and tenants. The innovation literature suggests, however, that the processes of technology development and adoption are more complex, with, as noted, positive feedbacks required between technology learning, entrepreneurial activity, development of relevant skills sets, and creation of legitimacy and public acceptability of the technology. In this project, we aim to shed light on the questions of consistency and compatibility between a large range of options, through further investigation of how these feedbacks could occur within the context of potential transition pathways.

A key dilemma for policy-makers is how to maintain appropriate levels of diversity amongst different low carbon options, whilst ensuring that promising options benefit from sufficient increasing returns and learning effects to enable them to challenge the dominant technologies (Foray, 1997; van den Bergh et al., 2006). This dilemma is heightened by possible incompatibilities between the measures and developments needed for large scale renewables and those for small scale renewables (Gross, 2008). This project will probe these issues by addressing a number of questions raised by the potential transition pathways:

- What developments in supply infrastructure, e.g. smart grids and grid access, would be needed for the wide deployment of small-scale renewables, and what issues do they raise in relation to the parallel development of supply infrastructure for large-scale renewables, e.g. grid extension?
- What are the overlaps or contradictions between measures needed to ensure the social acceptability of large-scale renewables, e.g. overcoming planning concerns, and those needed to ensure the social acceptability of small-scale renewables, e.g. encouraging the development of energy service companies and/or the greater involvement of consumers in their own energy service provision?
- What issues arise for the creation of the positive feedbacks needed for successful simultaneous innovation in a large range of technologies, given that

there is likely to be strong competition and potential incompatibility between a number of these technological options?

The project team will be pleased to receive feedback on the outline transition pathways described in this paper, and the extent to which key issues have been identified. Future papers will report on the project's findings in relation to addressing these questions.

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