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Developing transition pathways for a low carbon electricity system in the UK

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ABSTRACT

This paper describes the approach to developing transition pathways for a low carbon electricity system in the UK, being pursued in a major new inter-disciplinary research project. The project aims (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 approach, which builds on the work of Dutch researchers on transitions and transition management using a multi-level framework of niches, socio-technical regime and landscape, as well as on other parts of the innovation systems literature. It also describes its application to several outline transition pathways to a low carbon energy system in the UK. The pathways embrace both the evolution of the physical and institutional infrastructure changes and the roles of both large actors, e.g. multinational energy supply and distribution companies, national governments, major investors, and small actors, e.g. households, innovators and entrepreneurs.

Key words: *Transition pathways, multi-level perspective, dynamic processes, technological innovation systems, UK energy system*

Running title: *Transition pathways for low carbon electricity*

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1. Introduction

This paper describes the approach to developing transition pathways for a low carbon electricity system in the UK, being pursued in a major new inter-disciplinary research project. The work seeks to understand and help facilitate transition pathways for the UK, by combining historical and scenario analysis with assessment of the technical feasibility and social acceptability of potential pathways, within a whole systems assessment framework. 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 integrated power and gas company E.ON UK, and consists of eight parallel, interacting workstreams, organized under three Themes. The paper describes the approach being pursued under Theme 1, to developing transition pathways. It examines key issues for the elucidation of these pathways, focusing on the relations between institutions and infrastructures, and the roles, influences and opportunities of large and small actors in the dynamics of transitions. This is reflected in an emphasis on using pathways to examine alternative plausible governance patterns for UK energy systems and how these could affect technological, institutional and social changes in these systems.

We seek to understand and contribute to potential future UK energy system transitions. 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, using a multi-level perspective, with elements from transition management, which show how purposeful actions by actors within systems can give rise to changes in technologies, institutions and infrastructures.

This paper presents an initial description of how the insights from the transitions approach will be developed and applied in our project. Section 2 sets out our approach to developing transition pathways, drawing on the multi-level perspective, section 3 describes the theoretical basis for specifying outline transition pathways, section 4 applies the approach to specifying outline transition pathways for UK energy systems, and section 5 provides a discussion and sets out the next steps for the project.

2. Approach to developing transition pathways

In seeking to develop transition pathways for UK energy systems, we are strongly driven by the desire from policy-makers and industrial and wider stakeholders for conceptual frameworks that enable the examination of plausible future pathways in ways that will inform current decision-making. Actors within these systems are increasingly driven by the need to meet challenging carbon emission reduction goals by the middle of this century. This implies radical and disruptive changes to current energy systems, to be achieved whilst maintaining ‘secure’ supplies and meeting ‘reasonable’ energy service demands at ‘affordable’ costs. The nature of these changes and what different actors judge to be secure, reasonable and affordable is highly contentious. Current energy scenario work largely focuses on technically plausible futures and their likely costs and benefits, often using modelling approaches that assume a high level of economic rationality of actors. Despite its useful insights, such work does not illuminate how technological changes arise through the dynamic interactions between a range of actors with different perspectives and goals. Their decisions and behaviour are likely to be key influences on how to get from 'here' to a radically different low-carbon 'there' – and need to be understood if effective policy strategies and instruments are to be developed. Our starting point is that frameworks developed to examine past system transitions and guide management of future transitions could usefully be applied to understanding the changing roles, influences and opportunities of actors, both large and small, in the dynamics of future energy transitions.

Our approach builds on the multi-level perspective (MLP) for analyzing the dynamics of transitions, developed primarily by Dutch researchers [1–4]. This 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*. The *landscape* 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* reflects the prevailing set of routines or practices that 'actors' and institutions use and that create and reinforce a particular technological system; these practices include: "engineering practices; production process technologies; product characteristics, skills and procedures […]embedded in institutions and infrastructures" [1]. Whereas the existing regime generates incremental innovation, radical innovations are generated in *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 and between these different levels.

Research under the transitions approach has developed along three main lines. Firstly, the multi-level perspective is used as a framework for the analysis of the historical dynamics of transitions. Thus, for example, Verbong and Geels [5] analysed the historical dynamics within the Dutch electricity system from 1960 to 2004 in this way. Secondly, the transitions approach has been used as a basis for developing 'transition management'. This is a process of governance that aims to steer or modulate the dynamics of transitions through interactive, iterative engagement between networks of stakeholders. The 'management' process involves creating shared visions and goals, mobilizing change through transition experiments, and learning and evaluation of the relative success of these experiments [6, 7]. Transition management is, therefore, a form of participatory policy-making based on complex systems thinking. A key element of this process is the creation of a 'transition arena', in which a relatively small group of innovation-oriented stakeholders can come together to engage in social learning about future possibilities and opportunities.

The third main line, particularly relevant for our approach, applies the multi-level perspective to develop 'socio-technical scenarios'. Such a scenario "describes a potential transition not only in terms of developing technologies but also by exploring potential links between various options and by analysing how these developments affect and are affected by the strategies (including policies) and behaviour of various stakeholders" ([37], p.6). Elzen, Hofman and colleagues have developed socio-technical scenarios to explore potential transitions to more sustainable systems in the Netherlands in the electricity domain [37, 30] and the passenger mobility domain [38].

Our theoretical approach to developing transition pathways is an elaboration of the socio-technical scenarios method, augmented by recent thinking in innovation systems and co-evolutionary research. The theoretical basis for linking these different methodologies, which builds on the work of Markard and Truffer [36], is described briefly in the next section of the paper. The argument for the methodological consistency of this approach is set out more fully in the project's conceptual and analytical framework [39].

In specifying plausible transition pathways for future development of UK energy systems, we focus on different pathways for the governance of these systems and their implications for the rates of innovation and technological developments needed. The description of the pathways aims to illuminate the following issues:

- What are the roles of different actors (large and small, public and private) in influencing the pathway?
- What are the key technological and institutional changes that are involved in each pathway, and what key engineering and social challenges arise?
- To what extent could the UK play a leadership role, in both technological and political terms, in relation to the rest of the world?

The content of our outline transition pathways to a UK low carbon energy system draws on the prior experience and expertise of the project team members, along with further information and insights gathered in the early stages of the project. Team members have contributed to a number of previously formulated scenarios for the future development of UK energy systems to 2050, including the SUPERGEN future network technologies scenarios [31] and highly distributed power systems scenarios [40], and scenarios developed using the UK MARKAL model to inform the 2007 Energy White Paper [32]. A wider review of UK and international energy scenarios has been conducted [41], and an initial set of interviews were conducted in May-December 2008 with 'gatekeepers' from the UK energy policy and industry communities. Facilitated discussions on the approach and specification of the pathways involving stakeholders from the policy-making, industry and academic communities were held at a workshop in November 2008. The critical insights generated at this meeting and further subsequent feedback from participants proved particularly useful. The outline pathways also draw on recent publications by the UK government and advisory bodies, including the UK Renewable Energy Strategy Consultation Document [42] and the first report of the UK Committee on Climate Change [43].

We are following an iterative process, both in developing our transition pathways and in building multi- and interdisciplinary working within the consortium. An initial set of outline pathways is being developed. These will then be investigated and compared using a range of modelling and assessment tools and criteria, both to assess their plausibility and to identify areas where more detailed specification is needed. This will include identification of endogenous decisions that are amenable to influence by UK actors, and those that are not, including key landscape changes or perturbations, for which exogenous assumptions will be made.

There are three main steps in our approach to identifying the initial outline transition pathways:

(1) *Characterise the existing energy regime, its internal tensions and landscape pressures on it*;

(2) *Identify dynamic processes at the niche level*; and

(3) *Specify interactions giving rise to or strongly influencing transition pathways*.

These three steps are applied in an iterative loop to specify these characteristics, processes and interactions at progressively greater detail. Section 3 describes the main theoretical concepts drawn on for each of these steps. Section 4 demonstrates how the steps are being applied in our initial specification of transition pathways for UK energy systems.

3. Theoretical basis for specifying outline transition pathways

This section sets out the theoretical basis used for specifying outline transition pathways. In addition to the multi-level perspective for examining transitions, we draw on recent research on technological innovation systems and co-evolutionary analysis. We argue that this gives a richer analytical basis for specifying pathways, situates our work in relation to other important ongoing research, and will lead to the specification of more useful and policy-relevant pathways. We describe this theoretical basis as it relates to the three main steps set out in the previous section.

(1) *Characterise the existing energy regime, its internal tensions and landscape pressures on it*

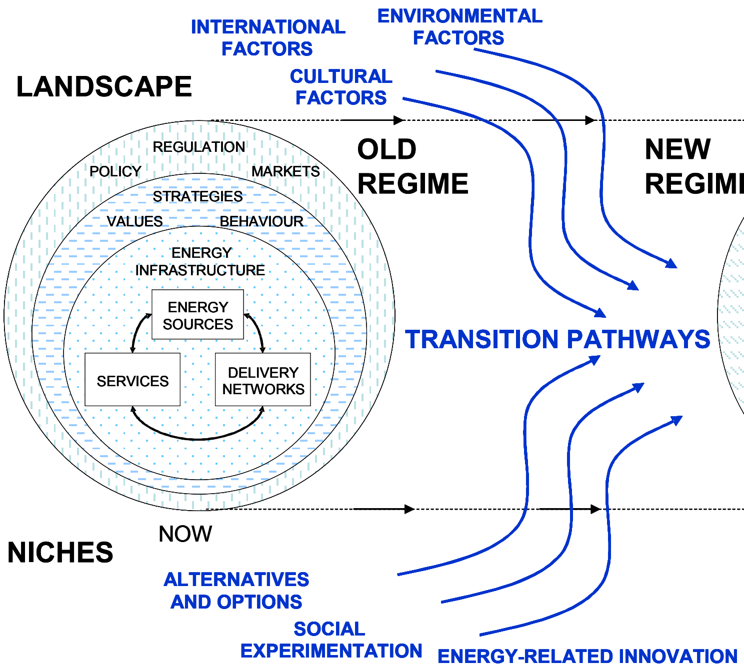

Figure 1: Possible Transition Pathways and the Factors that Influence them (Source: Transition pathways project team)

To establish potential future transition pathways in UK energy systems, we first need to characterize key elements of the existing regime, as well as identify key processes influencing the dynamics of change and stability (summarized in Figure 1, where the different shadings represent different configurations at the start and end of the transition). We begin by characterizing the socio-technical regime that meets energy service demands by households, businesses and organizations. These services include lighting, heating, cooling and the use of electrically powered appliances. (The regime for meeting mobility/transport services is currently largely separate, though in some future pathways, these regimes may become more intertwined, e.g. via plug-in and/or hybrid electric vehicles.) These demands are met through delivery networks which transfer power and energy from energy sources embedded in energy infrastructures. Three main physical infrastructures underpin UK energy service delivery, namely the national electricity and gas transmission and distribution networks and the buildings infrastructure, a key determinant of the levels of service demand.

A diverse range of actors and networks lie within the electricity regime. Following Verbong and Geels [5], we focus on households, large industrial users, energy supply companies, distribution network operators, transmission system operators, electricity generators, national government, and regulators. These actors' behaviours may be characterized by the values they hold, the resources they command, and the strategies they choose to follow. These are in turn influenced by the institutional factors of national policies, market rules, and regulatory structures.

Following the multi-level perspective, the regime is also influenced by wider landscape factors and alternatives and options developing in niches [1−4]. Landscape factors 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 concerns about energy affordability and fuel poverty, and factors which threaten physical disruption of external supplies (war, terrorism, foreign governments limiting supply, etc.), as well as changes in the international economic and financial situation. Alternatives developing in niches include the demonstration of new technological options, new ways of organizing systems for meeting energy service demands and new ways of adapting energy-using behaviour [6].

(2) *Identify dynamic processes at the niche level*

The second step is to identify key processes that influence dynamics and stability. We take a broad co-evolutionary view of change and stability, in which dynamics are determined by causal influences between mutually evolving systems. For example, Freeman and Louca [8] 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. Several recent studies have used an analytical framework based on the co-evolution of technological systems, institutions and business strategies [9−12, 52]. We follow a similar framework, but also include analysis of user practices, in terms of the desirability of particular technological and system organization alternatives, incorporating both psychological and sociological perspectives on energy use behaviour [44]. Hence, the formulation of transition pathways focuses on processes relating to the co-evolution of technological systems, institutions, business strategies and user practices.

These processes arise through interactions between activities at the niche, regime and landscape levels. The multi-level perspective has been criticized for being "too descriptive and structural, however, leaving room for greater analysis of *agency* as a means to more informed, deliberate and effective processes of regime transformation" ([17], p.1492). As we are particularly interested in radical innovation processes and how they challenge the existing regime, we draw on a well-developed body of literature on technological innovation systems. A technological innovation system (TIS) may be defined as a "network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology" ([45], p.111). Thus, a technological innovation system provides the social and institutional context for the activities of actors at a niche level involved in the generation and diffusion of new technologies and new organizational alternatives. The conceptual relations between the multi-level perspective and technological innovation systems have been clarified by Markard and Truffer [36]. They argue that the innovation system concept provides a richer and more analytically powerful tool for examining the processes by which niche-level activities challenge the incumbent regime. They view a TIS as encompassing a variety of different actors pursuing different innovation strategies and/or controlling different sets of resources, but united by shared expectations or a shared vision for the respective innovation field. Thus, a TIS may encompass several niches or application contexts.

The work on functions of technological innovation systems is a particular analytical strength of the TIS concept. These functions are key dynamic processes that have been identified as requirements for 'well-performing' innovation systems, i.e. those with a high rate of new and economically useful innovations that challenge incumbent technological systems. We apply the functions or dynamic processes identified by Hekkert et al. [13], building on the earlier work of Jacobsson and Bergek [14]. These functions or dynamic processes are: *entrepreneurial activities; knowledge development; knowledge diffusion through networks; guidance of search activities; market formation; mobilization of resources;* and *creation of legitimacy/ overcoming resistance to change*.

Entrepreneurial activities cover both new entrants seeking business opportunities in new markets, and incumbent companies which diversify their business strategy to take advantage of new developments, in either case giving rise to experiments and learning. *Knowledge development* includes R&D projects, patenting of new ideas and investments in R&D, also leading to learning within the system. *Knowledge diffusion through networks* includes exchange of information between the different actors within the system and the networks through which they interact. *Guidance of search activities* refers to activities relating to selection between different technological options, and includes interactive and cumulative processes of exchanging ideas between users, producers and other actors, giving rise to changes in user practices and the creation of positive expectations about the future potential of the technology. *Market formation* includes activities that stimulate the creation of niche markets, either through entrepreneurial and learning activities, user demands, or specific policy incentives and measures. *Resources mobilization* includes investment in both financial capital and human capital involving the accumulation of relevant skills and capacities. *Creation of legitimacy* includes the action of advocacy coalitions to promote the adoption of new alternatives, and also responses to counter-actions by incumbent players seeking to maintain their current advantage.

In line with the co-evolutionary view of change and stability, technological change occurs through the creation of 'virtuous cycles', in which successful activities within one process enable other processes to succeed, i.e. a process of cumulative causation [12, 13]. For example, an increase in entrepreneurial activities may stimulate development of new knowledge and increases in lobbying and advocacy activities, creating higher expectations and guiding the search patterns of other actors.

As noted, the analysis of these processes has generally focused on technological change, but within the context of innovation systems which incorporate wider social, institutional and cultural factors. In this way, changes in institutions, i.e. social rules and structures including market rules, regulatory systems and national policies, are seen to be crucial determinants of these dynamic processes that lead to technological change. Hekkert et al. [13], responding to critiques of innovation systems and multi-level transitions analyses as being overly institutionally or structurally deterministic, argue that interpreting functions of innovation systems as dynamic processes or activities recovers a role for the entrepreneurs and other actors to actively influence change. They are then able to map activities or key events within a process of technological change, and show how structural factors and activities mutually influence each other [16].

(3) *Specify interactions giving rise to or strongly influencing transition pathways*

Following the multi-level perspective, transition pathways are defined by the interactions between the internal regime dynamics and wider landscape factors and niche alternatives, which destabilize the incumbent regime and eventually give rise to a new regime.

Two typologies have been proposed to characterize how differences in the timing and nature of multi-level interactions can give rise to different transition pathways. Smith et al. [17] characterize regime change as a function of two processes: (1) shifting selection pressures on the regime, coming from social and economic pressures within the regime, and broader landscape developments and niche innovations; (2) the co-ordination of resources available inside and outside the regime to adapt to these pressures. Their typology of transitions then depends on two dimensions: (i) the extent to which the resources enabling regime adaptation come from inside or outside the incumbent regime; (ii) the extent to which the deployment of these resources is co-ordinated or unco-ordinated [18]. This gives rise to a typology of four transitions, as follows:

- *Endogenous renewal (co-ordinated response, internal adaptation)*: This arises in the context of regime members (firms, supply chains, customers and regulators) making conscious efforts to find ways of responding to perceived competitive threats to the regime, by drawing on internally available resources, such as existing capacities.
- *Re-orientation of trajectories (uncoordinated response, internal adaptation)*: This type of transition arises through the conjunction of a series of uncoordinated responses, relating to changes in technologies, institutions, business strategies and user practices, but mainly drawing on internally available resources.
- *Emergent transformation (uncoordinated response, external adaptation)*: This type of transition arises largely from uncoordinated pressures for change and responses based on through resources and capacities lying outside the incumbent regime, such as previous energy transitions between dominant fuel sources, e.g. from wood to coal burning.
- *Purposive transitions (co-ordinated response, external adaptation)*: This type of transition also draws on external resources, but has been deliberately intended and pursued from the outset to reflect an explicit set of societal expectations or interests, such as the promotion of civil nuclear power.

Geels and Schot [19] criticized this typology, as in their view, co-ordination arises through the alignment of the visions and activities of different groups, and hence can not be regarded as lying on a single axis to characterize transitions. Instead, they propose a different typology, based on differences in the timing and nature of multi-level interactions, as follows:

- *Transformation path*: This occurs when actors in the existing regime modify the direction of development paths and innovation activities in response to moderate landscape pressures and niche-innovations not yet sufficiently developed;

- *Reconfiguration path*: Groups of innovations, developed in niches, are initially adopted in the regime to solve local problems, and subsequently trigger further adjustments in the basic architecture of the regime;

- *Technological substitution*: This occurs when a disruptive change or shock(s) at the landscape level destabilizes the existing regime, and enables previously developed niche-innovations to break through and replace the existing regime;

- *De-alignment and re-alignment path*: This occurs when divergent, large and sudden changes at the landscape level lead to de-alignment and erosion of the existing regime, but niche-innovations are not sufficiently developed, and so multiple niche-innovation co-exist and compete for resources until one becomes dominant.

Shackley and Green [20] used this typology to analyse past UK transitions and to outline potential future transitions to low carbon energy systems. They argue that the *reconfiguration* and *de-alignment/re-alignment* paths are the most likely for future low-carbon energy transitions in the UK because of the rapid disruption likely to be caused by landscape pressures relating to climate change mitigation and energy security concerns, combined with the relatively early stages of development of current low carbon niche-innovations. Geels and Verbong [21], in their paper in this special issue, also apply this typology to potential future pathways for sustainability transitions in the Dutch electricity sector.

Whilst these typologies are useful in thinking about how the different elements of a transition path may interact, in our work we choose not to specify the global nature of a potential future transition from the outset. Instead, we examine pathways based on alternative plausible governance patterns for UK energy systems and how these patterns could affect technological, institutional and social changes in these systems. 'Governance' refers to how the interactions between choices made by different actors within the system, including national and local policy-makers, large firms and new entrants, financial investors and end-users, give rise to changes to the system (Smith, 2009). This approach enables us to explore how social and political issues, such as public acceptability of different technologies and institutional changes, the mixture of short-term and long-term drivers and influences affecting policy-making, and the strategies of large and small firms, interact or 'co-evolve' with present and expected future changes in technologies. The actors within the system have a range of individual and social goals, including the pursuit of personal and corporate advantage, the supply and provision of energy services at reasonable costs, maintaining security of supply, and contributing to wider social and environmental aims, which may often conflict in practice. Particular institutional arrangements strongly influence the governance of energy systems and consequently frame the ways in which these conflicts are resolved. In turn, the institutional arrangements and governance processes shape the patterns of technological change that arise. As we develop our transition pathways, we will re-examine whether and how they resonate with the above typologies.

4. Specifying outline transition pathways for UK energy systems

This section describes briefly the application of this approach to specifying outline transition pathways for UK energy systems. Our focus is on transition pathways to low carbon energy systems. The scale of this challenge is set by the legally-binding commitment to reduce the UK's greenhouse gas emissions by at least 80% by 2050, compared to 1990 levels, made by the UK Government in the Climate Change Act 2008 [22]. The Government has also formed a new institution, the Committee on Climate Change, consisting of external energy and climate experts, to recommend five-year carbon budget periods towards the target, beginning with budgets for the periods 2008-12, 2013-17 and 2018-22 [43]. We do not start by assuming that any or all of our pathways will meet the 80% target by 2050. We assume, however, that the strengthening scientific basis for human-induced climate change and its impacts [23], as well as the economic case for urgent action advanced in the Stern Review [24], will result in the UK continuing to put in place policies and measures designed to move towards a domestic emissions reduction target of the order of 80%, as well as actively contributing to negotiations on international targets and agreements. The extent to which UK carbon budgets can be plausibly met by UK domestic emissions reductions will influence both the need to purchase additional carbon credits relating to overseas emissions reductions, e.g. under the Clean Development Mechanism, and the government's continuing willingness to achieve its targets.

As human contributions to climate change are determined by cumulative emissions and not by arbitrary end-points [25], we will also investigate the cumulative emissions profile of our pathways. Hence, the timing and degree of successful implementation of policies and measures will be an important feature of the pathways.

Although our approach to pathway formulation is more widely applicable, in this project we focus on pathways in which electricity is the dominant vector for energy transmission. This provides an appropriate boundary, whilst incorporating a range of important future possibilities, including the potential for the increased use of electricity to provide heating and vehicle propulsion services. We will also investigate different technological configurations, including the relative importance of electricity systems that are centralized or decentralized, not least because strong reliance on either approach seems likely to give rise to issues of path dependency [47].

(1) *Characterise the existing energy regime, its internal tensions and landscape pressures on it*

The current UK electricity regime for meeting lighting, heating and power-related services may be characterized as a centralized system. Electricity is centrally generated, largely from natural gas, coal, nuclear and a small but growing set of renewable sources; it is 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, imported via pipelines or in the form of 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 electricity and gas markets were privatized and liberalized in the 1990s, to facilitate competition between electricity generators, and between companies supplying electricity and gas to homes and businesses, overseen by an economic 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, which focuses on ensuring secure and affordable supplies, and meeting other social and environmental objectives (it is notable that since the mid 1990s, successive governments have placed increasing emphasis on climate change and its regulation, an issue that did not feature in the Electricity Act that preceded the 1990 electricity privatisation [48]).

Key processes that influence or 'drive' the energy regime at the landscape level 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 the promotion of low carbon energy sources;
- ideological commitments to liberalized energy markets;
- concerns over security of primary energy supplies;
- external factors leading to high and/or volatile oil and gas prices;
- related concerns over energy affordability and fuel poverty;
- factors which could lead to physical disruption of external supplies (war, terrorism, foreign governments limiting supply);
- changes in the international economic and financial situation, such as those associated with the current 'credit crunch'.

The dominant processes at present (early 2009) are governmental commitment to national and international targets for moving to a low carbon energy system and concerns over security of supply, against a backdrop of the 'credit crunch'. As noted, in the Climate Change Act, which became law in November 2008, the UK government committed itself to achieving at least an 80% reduction in greenhouse gas emissions by 2050, with an interim target of a 26-32% reduction by 2020. The earlier target, a 60% reduction in CO_2 emissions, was first formally made in the 2003 Energy White Paper, but without any strong supporting institutional structure to ensure a pathway to this target [26]. The target was strengthened to an 80% reduction in response to the increasingly disturbing scientific predictions, the rapidly increasing public awareness of the issue and the analysis provided by the UK Treasury's Stern Review [24]. This review 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 potentially influential Climate Change Committee will make the government more accountable, so that stronger pressures on the energy regime are likely to result.

In addition, the UK has signed up to, and was one of the drivers of, the European Energy and Climate Policy Package, finally agreed at the Council of Ministers in December 2008. 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 agreement for how this latter target is to be shared out between countries sets a UK target of 15% of final energy from renewable sources [27]. This target will be very challenging, as until very recently UK renewables policy has largely focused on electricity generation, with little attention to renewable heat or transport. In June 2008, a Government Consultation Paper on meeting this target, estimated that it would require 30-35% of electricity to be generated from renewable sources by 2020 [42]. This compares starkly with the current goal of 20% renewable generation by 2020 and firm incentives through the Renewables Obligation to achieve 15% by 2015. Hence, if the Government is to achieve its recent commitments, the relative stringency of 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. Part of the Government's response to landscape pressures has been the setting up in 2008 of a new Department of Energy and Climate Change, which brings together elements of the energy and environmental portfolios that were formerly located in the separate environment and industry ministries (Defra and BERR).

The second main driver of UK energy policy at the landscape level is concerns over security of primary energy supplies. A variety of factors anticipated between now and 2020 have led to a perceived electricity generation 'gap' and concerns about availability of primary energy sources to enable it to be filled, whilst also achieving carbon reduction targets. These influences include: prospects of 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. The response has led to pressures on the electricity regime, in the form of renewed support in principle for the building of new nuclear power stations [28] and consent for new coal-fired power stations. These policies have also been strongly driven by lobbying from actors within the existing regime, as they try to maintain the current centralized generation system and their role in it.

Other strong drivers within the existing regime are recent increases in electricity and gas prices for households and industry, flowing from increases in international oil and gas prices; growing concerns over energy affordability and fuel poverty; and changes in users' responsiveness to higher prices. At the same time, increasing public concerns over climate change could translate into growing willingness to accept and undertake change in response. At the moment (early 2009), both government 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 will require energy suppliers to stimulate take-up of low carbon and energy efficient measures by their customers. This could lead to significant changes in business strategies for large industry players, particularly if they face challenges from new entrepreneurial energy service companies.

The recent changes in the international economic and financial situation, associated with the ongoing 'credit crunch', and their manifestation within the UK could exert significant pressures on the regime: on demand and international energy prices, because of lower economic growth; on the willingness of governments to support and companies to invest in or supply low carbon technologies; and, after the experience of government engagement with banks, on the nature of the government's role in the regulation and ownership of private sector enterprises.

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 industrial stakeholders, led by one of the authors, 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 [29].

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

(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. They include both relatively large-scale 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 relatively small-scale 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 and air-source heat pumps. As envisioned within the de-alignment/re-alignment pathway, 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.

For those technologies identified to be significant within any pathway, the fulfillment of the functions of the related technological innovation system will be examined, together with the feedbacks between these functions that could lead to the creation of 'virtuous cycles' in a process of cumulative causation [12, 13].

(3) *Specify interactions giving rise to or strongly influencing transition pathways*

As noted, our outline transition pathways focus on alternative plausible governance patterns for UK energy systems and how they could affect technological, institutional and social changes in these systems. The governance patterns relates to the mix and balance of actions led by central government, actors in liberalized markets and civil society actors. This creates a broadly defined 'action space' in which the current energy regime sits[1]. Depending on which of these kinds of actors is deemed to have most 'power', different kinds of relationships between actors exist and different forms of transition may develop. Reflecting on these relationships through this interpretive lens thus holds the potential of providing insights on how the initial phases of transition pathways may play out within the current energy regime, and how different actors are likely to react to transition processes. We also use the pathways to explore the mix and balance of centralized and decentralized decision-making within energy systems, in which power is exercised by a small number of large actors or a large number of small actors. The specification of these pathways draws on the experience of the project team, and the insights provided by the stakeholders at the workshop and through the 'gatekeeper' interviews. Our initial outline pathways are as follows.

The first pathway, *Market Rules*, envisions the broad continuation of the current market-led governance pattern. Here, the government specifies the high level goals of the system and sets up the broad institutional structures, in an approach based on minimal possible interference in market arrangements, which are held to be the most effective and efficient mechanism for energy service delivery. As anticipated, this perpetuates the present centralized generation system in which energy services are supplied mainly by large, vertically integrated firms. The underlying philosophy also allows for overseas investment to count towards UK targets, through the use of Joint Implementation, the Clean Development Mechanism and other flexible mechanisms. Stresses will become evident in this pathway, however, including whether sufficient investment is made in appropriate skills and technological capabilities to enable UK domestic emission reduction targets to be met, and whether the incentives for market actors are sufficient to induce them to deliver on challenging government targets for reducing carbon emissions.

The second pathway, *Action/Reaction*, which might also be interpreted as a bifurcation of *Market Rules*, envisions the continuation of the current governance pattern in the short

[1] We are grateful to our colleagues Jacquie Burgess and Tom Hargreaves for suggesting and elaborating the concept of an 'action space'.

term, but then a failure of the centralized system to deliver on energy security and climate change goals leads to renewed interest in decentralized systems, together with a greater focus on energy saving and the development of energy service companies. This could occur through stronger governmental intervention, driven by the need to deliver on agreed climate change targets and concerns over short-time maintenance of supplies, and by resources freed up by decline in investment in centralized options being focused on the scaling up of decentralized options which have previously flourished in niche markets. Concerns raised by this pathway include whether starting down a more centralized route will have significantly delayed investment in decentralized options and their widespread acceptance.

The third pathway, *Central Control*, envisions greater direct governmental involvement in the governance of energy systems. This could involve the setting up of a government-owned or funded 'Strategic Energy Authority' and/or the use of central contracts for the delivery of new low carbon generation, including nuclear power, offshore wind and coal with CCS. The initial focus would be on overcoming perceived blockages in the current system, by addressing transmission constraints, planning issues, supply chains and skills, and introducing non-behavioural measures on the demand side, including increasing energy efficiency standards on products and new build housing. By leading on these measures and providing strong 'technology push' on offshore technologies and CCS for UK industrial as well as climate benefits, these actions would then legitimate further governmental steps to influence lifestyles and behaviours. However, there would concerns in this pathway relating to governments trying to 'pick winners', i.e. to anticipate which technologies will be significant in mitigating climate change, and that this would be done on the basis of political factors, such as perceptions of national competitiveness or industry lobbying, rather than techno-economic assessments of potential contributions.

The fourth pathway, *Thousand Flowers*, envisions a sharper focus on more local, bottom-up diverse solutions ('let a thousand flowers bloom'). These developments are driven by innovative local authorities and citizens groups, such as the Transition Towns movement [49], to develop local micro-grids and energy service companies. A variety of more locally based technological and institutional solutions then begin to spring up, challenging the dominance of the existing large energy companies. The concerns in this pathway would relate to whether these types of bottom-up solutions could evolve into sufficiently strong and coherent alternatives to be able to challenge the dominance of the mainstream actors and institutional structures in the current regime.

The project team is currently undertaking a second iteration of the specification of these pathways. In this second iterative loop, we are undertaking an initial 'ball-park' quantification of the existing regime dynamics and the dynamic processes at niche levels, for each of the initial outline transition pathways. This will lead to a fuller specification of these outline pathways, including exploration of the extent to which the identified limiting factors are likely to delay or inhibit the achievement of carbon emissions reduction targets within each pathway.

5. Discussion and Next steps

This paper has set out the theoretical and methodological basis for the specification of outline transition pathways to a low carbon, electricity-led energy system in the UK. This has been exemplified by a brief discussion of our initial specification of outline transition pathways, which focuses on alternative plausible governance patterns for UK energy systems and how these could affect technological, institutional and social changes in these systems. We argue that our approach both contributes to theoretical and methodological debates on specifying transition pathways, and will be useful in informing policy-makers and other stakeholders. The theoretical contribution relates to the incorporation of recent ideas about how the analysis of technological innovation systems can be integrated into the mutli-level perspective of *landscape, regime* and *niches.* We argue that this will provide a richer analytical basis for the development of transition pathways than was the case for previous work on socio-technical scenarios. The policy-relevant contribution relates to the integration of technological and social science analyses into the specification and examination of these pathways. We argue that this will go beyond much recent work on UK energy scenarios that has largely focused on examining technically plausible futures and their likely costs and benefits, often using modelling approaches that assume an implausibly high level of economic rationality of actors, while taking relatively limited account of interactions between them. We conclude by briefly describing the next steps to be taken by the project team in examining the outline transition pathways, under three project Themes.

Theme 1 (*Transitions, scenarios and historical analysis*) will complement the above analysis with insights for transition pathways from existing scenarios for development of UK energy systems to 2050 [31–33, 41], and from historical analysis of long-term developments in use and costs of energy services arising from technological and social changes [34, 35, 50, 51]. Theme 2 (*Technical and social analysis of supply-side, demand-side and infrastructure networks*) includes examining the technical feasibility of pathways using electricity network models, and exploring their social acceptability using participatory and deliberative methods. The latter will involve the use of semi-structured interviews with relevant actors, including households and SMEs, to inform how demands for alternative technological, organizational and behavioural options might be generated. Theme 3 (*Systems Appraisal and Joint Working, Integration and Learning*) will provide a whole-systems assessment of the pathways within a sustainability (technical, environmental, economic and social) framework. This will be used to identify key constraints and 'tipping points' which might limit or enhance the potential transition pathways. Further interactions with public and private stakeholders in future stakeholder workshops will help test and refine the developed transition pathways and related whole-systems assessments. The 'final' pathways and assessments, and the participative processes used in their development, should contribute to ongoing UK and international energy policy debates about the actions and institutional changes needed for a transition to a low carbon energy system.

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REFERENCES

[1] A. Rip and R. Kemp (1998), "Technological change", in Human Choices and Climate Change, Vol. 2, ed. S. Rayner and E.L. Malone*, Battelle Press, Columbus, Ohio*.

[2] F. Geels (2002), "Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study"*, Research Policy* 31, 1257-1274.

[3] F. Geels (2005), *Technological Transitions and System Innovations: A Co-evolutionary and Socio-Technical Analysis*, Edward Elgar, Cheltenham.

[4] R. Kemp (1994), "Technology and the transition to environmental sustainability: the problem of technological regime shifts", *Futures* 26, 1023-1046.

[5] G. Verbong and F. Geels (2007), "The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004)" *Energy Policy* 35, 1025-1037.

[6] R. Kemp and J. Rotmans (2005), "The Management of the Co-Evolution of Technical, Environmental and Social Systems", in M. Weber and J. Hemmelskamp (eds.), *Towards Environmental Innovation Systems*, Springer Verlag, Berlin.

[7] D. Loorbach (2007), *Transition Management: New mode of governance for sustainable development*, International Books, Utrecht, the Netherlands.

[8] C. Freeman and F. Louca (2001), *As Time Goes By*, Oxford University Press.

[9] R. Nelson (1994), "The co-evolution of technologies, industrial structures, and supporting institutions", *Industrial and Corporate Change*, 3(1), 47-63.

[10] R. Nelson (2005), *Technology, Institutions and Economic Growth*, Harvard University Press.

[11] J. P. Murmann (2003), *Knowledge and Competitive Advantage: The Coevolution of Firms, Technology and National Institutions*, Cambridge University Press.

[12] T. Stenzel and A. Frenzen (2008), "Regulating technological change - The strategic reactions of utility companies towards subsidy policies in the German, Spanish and UK electricity markets", *Energy Policy*, 36 (7), 2645-2657.

[13] M. Hekkert, R. Suurs, S. Negro, S. Kuhlmann and R. Smits (2007), "Functions of innovation systems: A new approach for analyzing technological change", *Technological Forecasting & Social Change* 74, 413-432.

[14] S. Jacobsson and A. Bergek (2004), "Transforming the energy sector: the evolution of technology systems in renewable energy technology", *Industrial and Corporate Change*, 13(5), 815-849.

[15] B-A. Lundvall (ed.) (1992), *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning*, Pinter Publishers, London.

[16] S. Negro, M. Hekkert and R. Smits (2007), "Explaining the failure of the Dutch innovation system for biomass digestion – A functional analysis", *Energy Policy* 35, 925-938.

[17] A. Smith, A. Stirling and F. Berkhout (2005), "The governance of sustainable socio-technical transitions", *Research Policy* 34, 1491-1510.

[18] F. Berkhout, A. Smith and A. Stirling (2004), "Socio-technical regimes and transition contexts", in B. Elzen, F. Geels and K. Green (eds.), *System Innovation and the Transition to Sustainability: Theory, Evidence and Policy*, Edward Elgar, Cheltenham.
[19] F. Geels and J. Schot (2007), "Typology of sociotechnical transition pathways", *Research Policy* 36, 399-417.
[20] S. Shackley and K. Green (2005), "A conceptual framework for exploring transitions to decarbonised energy systems in the UK", *Energy* 32, 221-236.
[21] F. Geels and G. Verbong (2008), "Pathways for sustainability transitions in the electricity sector: Multi-level analysis and empirical illustration", Paper presented at Session: Transitions and Transition Management at International Conference on Infrastructure Systems, Rotterdam, 10-12 November 2008.
[22] Her Majesty's Government (2008), *Climate Change Act*, Her Majesty's Stationery Office, London, November 2008.
[23] Inter-governmental Panel on Climate Change (IPCC) (2007), *Climate Change: Fourth Assessment Report*, Cambridge University Press.
[24] N. Stern (2007), *The Economics of Climate Change: The Stern Review*, Cambridge University Press.
[25] K. Anderson and A. Bows (2008), "Reframing the climate change challenge in the light of post-2000 emission trends", *Philosophical Transactions of the Royal Society A*, Vol: 366. No.: 0. pp 3863-3882.
[26] T. J. Foxon and P. Pearson, (2007), "Towards Improved Policy Processes for Promoting Innovation in Renewable Electricity Technologies in the UK", *Energy Policy* 35, 1539-1550.
[27] European Commission (2008), *Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources*, COM(2008) 19 final.
[28] Department for Business, Enterprise and Regulatory Reform (BERR) (2008), *Meeting the Energy Challenge: A White Paper on Nuclear Power*, January 2008.
[29] G. P. Hammond and R. Waldron (2008), "Risk assessment of UK electricity supply in a rapidly evolving energy sector", *Proc. Inst. Mech. Eng. Part A: Journal of Power and Energy*, **222**(7), 623-642.
[30] P. Hofman, B. Elzen and F. Geels (2004), "Sociotechnical scenarios as a new tool to explore system innovations: Co-evolution of technology and society in the Netherlands' energy system", *Innovation: Management, Policy and Practice* 6, 2: 344-360.
[31] I. Elder, G. Ault, S. Galloway, J. McDonald, J. Kohler, M. Leach and E. Lampaditou (2006), "Electricity network scenarios for Great Britain in 2050", in *Future Electricity Technologies and Systems*, (eds. T. Jamasb, W.J. Nuttall and M.G. Pollitt), pp. 24-80, Cambridge University Press.
[32] N. Strachan, R. Kannan ans S. Pye (2008), "Scenarios and Sensitivities on Long-Term UK Carbon Reductions using the UK MARKAL and MARKAL-Macro Energy System Models", UKERC Research Report, available at http://www.ukerc.ac.uk/Downloads/PDF/S/Scenariosreport.pdf
[33] WWF, IPPR and RSPB (2007), *80% Challenge: Delivering a low-carbon UK*, Research Report, available at http://www.ippr.org/publicationsandreports/publication.asp?id=573
[34] R. Fouquet and P. J. G. Pearson (2003), "Five Centuries of Energy Prices", *World Economics*, 4(3), 93-120.
[35] R. Fouquet and P. J. G. Pearson (2006), "Seven Centuries of Energy Services: The Price and Use of Light in the Kingdom (1300-2000)", *The Energy Journal*, 27(1), 139-177.
[36] J. Markard and B. Truffer (2008), "Technological innovation systems and the multi-level perspective: Towards an integrated framework", *Research Policy* **37**, 596-615.

[37] B. Elzen, F.W. Geels, and P.S. Hofman (2002), *Sociotechnical Scenarios (STSc): Development and evaluation of a new methodology to explore transitions towards a sustainable energy supply*, Enschede, Netherlands: University of Twente, CSTM.
[38] B. Elzen, F.W. Geels, P.S. Hofman and K. Green (2004), "Sociotechnical Scenarios as a Tool for Transition Policy: an Example from the Traffic and Transport Domain", In B. Elzen, F.W. Geels, & K. Green (Eds.), *System Innovation and the Transition to Sustainability – Theory, Evidence and Policy*, Cheltenham: Edward Elgar.
[39] T.J. Foxon (2008), "Transition Pathways to a Low Carbon Economy: Conceptual and Analytical Framework", available at www.lowcarbonpathways.org.uk
[40] C. Jardine and G. Ault (2008), "Scenarios for examination of highly distributed power systems", *Proc. IMechE Part A: J. Power and Energy*, Vol. 222 (7), pp. 643-655
[41] N. Hughes and J. Mers (2009), "Review of UK and International Energy Scenarios", *Transition Pathways/UKERC Scenarios Working Paper*, King's College London.
[42] Department for Business, Enterprise and Regulatory Reform (BERR) (2008), *UK Renewable Energy Strategy: Consultation Document*, June 2008, http://renewableconsultation.berr.gov.uk/
[43] Committee on Climate Change (2008), *Building a low-carbon economy - the UK's contribution to tackling climate change*, First Report, December 2008, The Stationery Office, London, available at http://www.theccc.org.uk/reports/
[44] M. Nye, L. Whitmarsh and T.J. Foxon (2009), "Socio-psychological perspectives on the active roles of domestic actors in transition to a lower carbon electricity economy", submitted to *Environment and Planning A*.
[45] B. Carlsson and R. Stankiewicz (1991), "On the nature, function and composition of technological systems", *Journal of Evolutionary Economics* 1, 93-118.
[46] A. Smith (2009), 'Energy Governance: The Challenges of Sustainability', in I. Scrase and G. MacKerron (eds.), *Energy for the Future: A New Agenda*, Palgrave Macmillan, Basingstoke, UK
[47] T.J. Foxon, G.P. Hammond and P.J. Pearson, (2008), "Transition pathways for a low carbon energy system in the UK: assessing the compatibility of large-scale and small-scale options", *Paper presented at 7th BIEE Academic Conference, St Johns College, Oxford, 24-25 September*.
[48] P.J. Pearson (2000), "Electricity Liberalisation, Air Pollution and Environmental Policy in the UK", Ch. 21 in G. MacKerron and P. Pearson (eds.), *The International Energy Experience: Markets, Regulation and the Environment*, Imperial College Press, London, 289-302.
[49] R. Hopkins (2008), "The Transition Handbook: From oil dependency to local resilience", Green Books, Totnes, Devon, available at http://www.transitiontowns.org/.
[50] H. Chalmers, N. Jakeman, P.J. Pearson and J.R. Gibbins (2009), "CCS deployment in the UK: what next after the UK Government's competition?", *Proceedings of the Institution of Mechanical Engineers, Part A, Journal of Power and Energy* (forthcoming).
[51] S.J. Bennett and P.J. Pearson (2009), "From petrochemical complexes to biorefineries? The past and prospective coevolution of liquid fuels and chemicals production in the UK", *Chemical Engineering Research and Design (ChERD)* (forthcoming).
[52] B. Parrish and T.J. Foxon (2009), "Sustainability entrepreneurship and equitable transitions to a low-carbon economy", *Greener Management International* **55** (Spring 2009), 47-62.