The Rise of Accelerated Energy Innovation and its Implications for Sustainable Innovation Studies:
A UK Perspective

Mark Winskel and Jonathan Radcliffe

'Accelerated energy innovation' has become a prominent aspect of energy policymaking in response to more urgent drivers for change. This paper charts the rise of accelerated energy innovation in the UK, and considers its possible implications for sustainable innovation studies and research-policy exchange. As manifest in the UK, accelerated energy innovation has a number of distinctive features: an emphasis on relatively short term dynamics (years rather than decades), a focus on cost reduction and deployment support for large scale technologies, and a central role for the private sector and public-private partnerships. We argue that because it is predominantly regime-led and continuity-based, accelerated energy innovation presents a challenge to niche-led, more disruptive theories of sustainable innovation (Transitions Studies and Technological Innovation Systems theory). We conclude that sustainable innovation studies – while maintaining its critical and reflexive stance – should more fully reflect the multiform dynamics of energy systems under urgency, across a broad spectrum of continuity-based and niche-led changes.

Keywords: energy policy, innovation theory, accelerated innovation

Introduction

This paper considers recent changes in the political and economic context for energy system change, associated changes in the dynamics of innovation in the energy sector, and the possible implications of these changes for sustainable innovation studies and innovation theory. Reviewing recent developments in the UK, it charts a rising emphasis in energy innovation policy and practice on relatively short term targets (years rather than decades), to support for large-scale deployment and cost-reduction rather than longer-term research and development, and to continuity-based change rather than more disruptive innovation. We characterise and interpret these changes as manifesting an 'accelerated energy innovation' imperative, and we suggest that they carry significant implications for energy innovation dynamics, governance and research.

'Accelerated innovation' has become an important term in contemporary energy policy debates – and some research studies. The term has a natural appeal for energy policymakers (and policy-engaged researchers) in the face of urgent, concurrent challenges: decarbonisation, supply security (or 'energy independence'), affordability, business development and economic growth. In this context accelerated innovation offers the compelling promise of more affordable change pathways, and it has been invoked in a number of prominent national and international policy and research contributions. The International Energy Agency (IEA) has repeatedly deployed the term (e.g. IEA 2010; 2011; 2012). In 2010 the IEA set up a dedicated project on Accelerated Energy Innovation, which concluded that 'the transition to a low-carbon economy clearly requires accelerating energy innovation and technology adoption' (IEA, 2011: 38). The Global Energy Assessment similarly concluded that 'substantial and accelerated innovation is essential to respond to the sustainability challenges of energy systems' (Grubler et al., 2012: 1711). The term has also featured prominently in US debates on energy futures (e.g. Anadón et al., 2010; PCAST, 2010; Henderson & Newell, 2011).

In this paper we consider the emergence and manifestation of accelerated energy innovation in the UK. While there have been a few UK policy and academic 'prescriptive' studies of the potential of accelerated energy innovation (e.g. Stern, 2007; Grubb et al., 2008; Winskel et al., 2011), our concerns here are more empirical, interpretive and reflexive: to trace the remaking of the UK energy innovation system in response to the perceived accelerated innovation imperative, and then consider its possible implications for sustainable energy innovation theory. We suggest that the accelerated energy innovation imperative emerged in the UK with the setting of highly ambitious, relatively short term policy targets for decarbonisation and renewables deployment in the late-2000s.

Although as yet more of a policy and strategy phenomenon than a material influence on energy system change (in terms, for example, of accelerated deployment of large scale technologies), the working-out of the accelerated innovation imperative has already seen the wholesale remaking of the institutions, governance and spending patterns of the UK energy innovation system. New organisations and networks – typically business-driven or public-private partnerships – have significantly changed energy innovation practice for both private and public researchers, and the role of innovation in wider energy system change. The UK has been a particular setting for the playing out of the accelerated energy innovation imperative, reflecting its weakened and heavily liberalised institutional base, a powerful decarbonisation policy driver and the influential role of private business in UK public policy (Kern, 2011; Anadòn, 2013). At the same time, the wider uses of the term suggests that it is an international phenomenon reflecting pressing global drivers on energy systems.

We propose that the UK case invites critical reflection within sustainable innovation studies, and the paper draws-out some of the possible implications of accelerated energy innovation for sustainable innovation studies. We suggest that because it is mainly a regime-led and continuity-based phenomenon, accelerated innovation presents a challenge for evolutionary theories such as Transitions Studies and Technological Innovation Systems theory which articulate predominantly niche-led theories of change. This resonates with other recent contributions within Transitions Studies on the heterogeneity of transition dynamics and regime agency, and on the need for an opening-up of sustainable innovation studies to different disciplinary perspectives. Like others in the sustainable innovation studies community, we consider research, policy and practice as related, co-evolving domains which aspire to interactive, mutual learning. In that spirit, we conclude that sustainable innovation studies – while maintaining its critical and reflexive stance – should more fully reflect the rise of accelerated energy innovation and the multiform dynamics of energy innovation across a broad spectrum of continuity-based and niche-led changes.

The paper combines an in-depth case study of a national energy innovation system with a detailed critical review of the sustainable innovation studies literature. Methodologically, the paper is based on a detailed desk-based review of official and 'grey' policy papers, an extensive and detailed review of the sustainable innovation studies literature, and on our own accumulated experiences working at research-policy-business interfaces in the UK energy system over the past decade.[1] The next section maps the development of accelerated energy innovation in the UK since 2005; this is followed by a review of the development of sustainable innovation studies, especially 'quasi-evolutionary', niche-led theories of change (Transitions Studies and Technological Innovation Systems theory); after this, an account is offered of the experiences of research-policy exchange in sustainable innovation studies in the Netherlands and the UK, and then a survey of recent debates in innovation studies on transition dynamics and regime agency, and also wider academic debate on accelerated energy innovation; the final section concludes and outlines a research agenda for accelerated energy innovation.

Accelerated Energy Innovation: The UK Case

The Emergence of Urgent Change Imperatives

The UK was one of the first countries to liberalise and privatise its energy sector. For a period of around twenty years, from the late-1980s to the late-2000s, the system was governed mainly by market actors (Helm, 2003; Skea et al., 2011). Over the course of the 2000s, market-based governance was gradually weakened as public policymaking re-emerged, but in the early-2000s, policy and regulatory interventions were modest. At the beginning of the decade the UK's Royal Commission on Environmental Pollution identified climate change as a radical challenge for the energy sector, and called for a 60% target reduction in UK CO_2 emissions (relative to 1990 levels) by 2050 (RCEP, 2000). Soon after, in the first comprehensive statement on UK energy policy since privatisation, the Government committed itself to this target (DTI, 2003).

The '60% by 2050' decarbonisation commitment, though it re-legitimised long-term steerage of the energy system by public policy, was modest in its political, economic and institutional implications over political and commercial time horizons. The Royal Commission and UK Cabinet Office both presented scenarios suggesting that it could be met largely by a gradual roll-out of energy efficiency measures and renewable energy technologies (RCEP, 2000; PIU, 2002). Deployment programmes for large-scale technologies such as nuclear power and carbon capture and storage (CCS) were *not* seen as central strands of the required policy response at this time, at least over the short to medium term. The UK's renewable energy policy ambition also remained relatively modest (20% of electricity consumed by 2020), and seen as likely to impose only marginal added system costs (Gross et al., 2006). Together, decarbonisation and renewables deployment policies exerted only moderate pressures for change at this time.

In the second half of the 2000s more urgent imperatives for energy system change emerged. While there is some dispute about the extent to which these were 'real' changes, as opposed to perceived changes reflecting interest-based politics (as discussed under 'Research-Policy Exchange in the UK', below), they nevertheless brought about significant changes in the style of energy policymaking – and energy innovation dynamics. In 2006, a UK parliamentary committee listed a confluence of international and domestic forces suggesting the need for more urgent and material policy interventions: internationally, rapidly growing carbon emissions and investments in fossil fuel generation technology, despite growing scientific evidence of climate change risks; domestically, stalled progress in emissions reductions and an emerging reliance on imported oil and gas, at a time of increasingly volatile international markets (HCSTC, 2006).

Reflecting this changed context the Government commissioned another major policy review. This review (DTI, 2006) and the policy statement that followed (HMG, 2007) both conveyed a much greater sense of urgency than their counterparts earlier in the decade. While maintaining the '60% by 2050' decarbonisation commitment, the Government now identified energy security as a key policy driver. Substantial private sector investment in generation plant and network infrastructure was now considered necessary over the relatively short term to 2020, as old generating plant stock was retired and the need for new infrastructure arose, and within this, prominent roles were now suggested for carbon capture and storage (CCS) and new nuclear power stations.

In 2008, the Labour Government increased the UK's decarbonisation commitment from 60% to 80% by 2050 (HMG, 2008), reflecting growing international concerns about climate change (the higher target was linked to an identified need for a 50% global emission reduction by 2050; CCC, 2008). An '80% by 2050' target implied a significantly more challenging decarbonisation trajectory, even over the short to medium term: scenarios suggested that it required the UK electricity system to become almost carbon-free by 2030 (CCC, 2008). At the same time, under the European Commission's *Renewable Energy Directive* (CEC, 2009), the UK agreed to a highly ambitious target of 15% of all energy consumed to be produced by renewables by 2020. Because renewable technologies are more readily deployable at scale in electricity generation than in transport or heating, scenarios for complying with the Directive involved renewables providing well over 30% of electricity produced in the UK by 2020 (HMG, 2009b).

Together, the *Climate Change Act* and *Renewable Energy Directive* heralded a significant move away from two decades of market-based governance toward policy-directed change. The Government's now set out the proposed means for policy delivery in a *Low Carbon Transition Plan* and *Renewable Energy Strategy* (HMG, 2009a; 2009b); both made clear the urgency of the energy system challenge, with over 30GW of new renewables capacity needed by 2020, mostly from onshore and offshore wind farms. After 2020, major supply-side contributions were anticipated from wind, nuclear power and fossil fuel plant using CCS, and also, an expanded, 'smarter' electricity grid. To enable these, the

Government proposed planning reforms for 'swifter delivery', and also, expanded domestic supply chains to capture local economic benefit (HMG, 2009a).

At the start of the 2010s, the UK's energy policy ambitions were pursued in broadly unaltered form by a new centre-right coalition government, despite a deepening economic crisis and large cutbacks in public spending. Indeed, the new Government reinforced the UK's decarbonisation commitment by accepting the Climate Change Committee's recommended target of a 50% reduction in greenhouse gas emissions by 2025, and an 'envisaged' 60% reduction by 2030 (HMG, 2011a). Detailed Government proposals for institutional and regulatory reform of the energy sector now came forwards – proposals with real consequence over political and corporate planning horizons (DECC, 2011a). The package of reforms was aimed at supporting around £110 billion investment in electricity generation and transmission by 2020 – more than double existing rates of investment.

Decarbonisation and renewables deployment targets, and the closure of old generation plant stock (partly driven by European emissions control regulations), suggested the need for almost 60GW of new electricity capacity by 2025 – equivalent to almost three-quarters of the UK's existing power generation plant stock (DECC, 2011b). In this context, the Government concluded that there was 'no reasonable alternative' to a massive re-investment in the UK's national, centralised system of electricity generation and transmission: '[we do] not believe that decentralised and community energy systems can lead to significant replacement of larger-scale infrastructure' (DECC, 2011b: 24).

Accelerated Innovation and the UK Energy Innovation System

More urgent drivers for energy system change did not translate automatically to an 'accelerated innovation' policy agenda. In practice, however, the absence of any readily deployable technologies at a rate or scale to realise the UK's energy policy ambitions meant that accelerated innovation became a corollary of accelerated system change, prompting the wholesale remaking of the

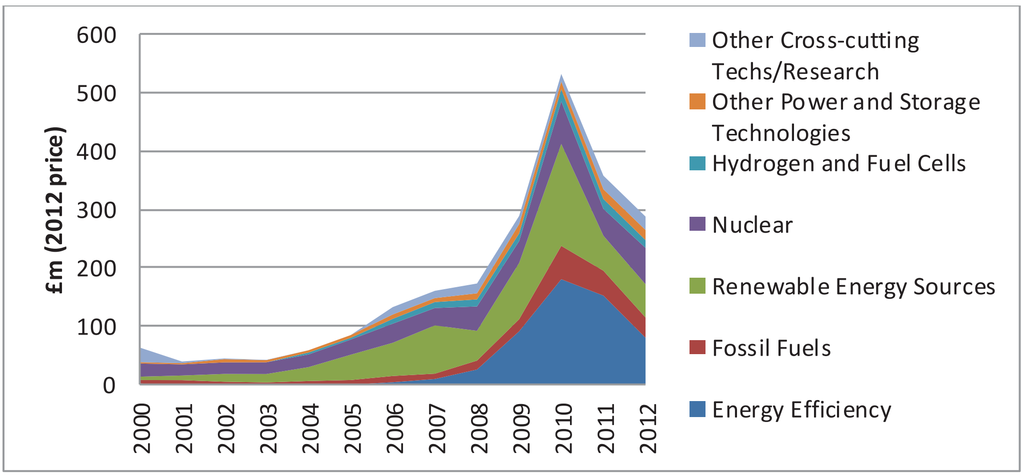

Figure 1. UK Public Spending on Energy Research, Development and Deployment (RD&D) (2000 to 2012) (IEA, 2013).

UK's energy innovation organisations and networks.

This remaking started from a very low base. The playing-out of market liberalism from the mid-1980s saw the dismantling of much of the UK's energy innovation system that had developed under public ownership. The privatised utilities had only a marginal strategic interest in technological innovation, and in the 1990s there was very little public investment in energy technology innovation (Figure 1); other than in the oil and gas sector, the same applied for the private sector (BIS, 2009).

As new policy drivers emerged in the 2000s, new energy innovation organisations and networks were created, but in the first half of the decade these were essentially grafted-on to an energy system which retained its orientation to short-run market imperatives (Winskel et al., 2006). The incentives and agencies established in this period, such as the Carbon Trust (CT), were oriented mainly to immature, long term technology prospects such as marine energy, consistent with then moderate wider policy ambitions (Scrace & Watson, 2009). As Kern (2012b: 308) noted, 'the dominant philosophy was to focus on competitive energy market governance at the regime level and to provide some funding for small-scale renewable niche technologies.'

In 2001 a Government Energy Research Review Group (ERRG) called for UK public spending on RD&D to be raised to bring it in line with that of European competitors, and also, for improved research co-ordination (ERRG, 2001). In practice, public spending levels remained low, and focussed mainly on longer term prospects rather than more readily deployable technologies; for more mature technologies, technology-neutral market-pull support was seen as the appropriate policy approach. Research co-ordination also remained weak: as the ERRG had suggested, a national Energy Research Centre was established, but as a small, distributed academic consortium rather than a single-site national centre. This was an essentially niche-based approach to energy innovation system building.

In the mid-2000s the UK's energy innovation system was more substantially remade in response to more urgent imperatives. Public investment began to rise (Figure 1) and a much greater role emerged for the private sector and public-private partnerships. An Energy Research Partnership (ERP) was set-up as a public-private strategy forum; an early ERP report called for clearer strategic vision, stronger coordination and more emphasis on technology demonstration (ERP, 2007). The late-2000s also saw the creation of the Energy Technologies Institute (ETI), a public-private partnership with significant resources, whose investments focussed on large scale engineering challenges such as offshore energy technology. The Technology Strategy Board (TSB), a public body with significant private sector representation, moved from an advisory role to become an investment agency; the TSB aims to 'accelerate economic growth by stimulating and supporting business-led innovation' (TSB, 2011a). It made energy innovation an early priority, spending on areas such as carbon capture and storage and offshore wind, and sponsoring the setting up of national innovation centres (known as 'Catapult Centres') for strategic technologies such as offshore renewables. The TSB defined the Centres' missions as 'provid[ing] an accelerated path for technologies to move from concept towards commercialisation (TSB, 2011b: 5).

The ETI and TSB also assumed important strategic roles in the newly-emerging energy innovation system. The Government described the ETI's remit as not only 'to accelerate the deployment of new low carbon energy technologies' but also, to provide strategic focus for the wider innovation system, including 'direction and pull' for university-based research supported by the Research Councils (DTI, 2007: 224-225). To help prioritise its investments, the ETI set about its own analysis of innovation priorities – undertaken largely in confidence to protect the interests of its private partners. The TSB also developed its own set of funding criteria, prioritising technologies which combined domestic industrial capability with global market opportunities (TSB, 2008).

In the late 2000s the energy industries' regulatory body, Ofgem, also built-up an internal analytical capability to consider the regulatory and investment implications of the Government's energy policy commitments (Ofgem, 2010a). Soon after, Ofgem's Low Carbon Networks Fund began sponsoring innovation projects for the renewal of the UK's national electricity and gas networks, marking a step-change in innovation spending on network infrastructure renewal (Ofgem, 2010b).

By the early 2010s, the UK energy innovation system had been aligned with the wider policy agenda for rapid system change. The remade innovation system (Table 1) was directed mainly at cost-reduction for the large-scale supply technologies seen as the main contributors to envisaged system change, and under the auspices of the TSB, cost reduction 'Task

Table 1. Main UK Public Funding Bodies for Energy Innovation (compiled by authors from multiple sources).

Organisation (date of inception)	**Stated Mission**	**Major Investments**	**Overall Spending**
Research Councils' Energy Programme (RCEP) (2006)	To position the UK to meet its policy targets and goals through high quality research and training.	Nuclear, conventional sources, renewables, end-use demand.	Research grants to universities and other institutions. £110m p.a. (2011-12).
Technology Strategy Board (TSB) (2008)	To stimulate innovation in areas which offer the greatest scope for UK growth and productivity.	Fuel cells, hydrogen; offshore renewables; grid; buildings; transport; materials	Grants to multi-partner collaborations, up to £35m p.a. on energy (2012-13).
Energy Technologies Institute (ETI) (2008)	To accelerate the development, demonstration and deployment of a portfolio of energy technologies.	Offshore renewables; networks; buildings; storage and distribution; heat; CCS, transport; bio-energy.	£60m p.a. (2008-18) from public and private funding.
Department of Energy and Climate Change (DECC) (2008)	To bridge the 'valley of death' between a technology being ready and it being widely deployed.	CCS; buildings, offshore renewables; manufacturing.	£50m p.a. from 2011.
Ofgem's Low Carbon Networks Fund (LCNF)(2010)	To help network operators provide security of supply at value for money in the move to a low carbon system.	Electricity and gas distribution networks.	Up to £100m p.a. (2010 – 2015).

Forces' were established for offshore wind and carbon capture and storage. This was a directed mission, charged with preparing the ground for wider system transition; as spelled out by the Government: 'in the 2020s we will run a technology race, with the least cost technologies gaining the largest market share. Before then, our aim is to help a range of technologies bring down their costs so they are ready to compete' (HMG, 2011: 1) The emphasis was on larger, co-ordinated efforts aimed at leveraging incumbent interests: in contrast with earlier initiatives, a regime-led innovation system.

Wider economic crises and a UK Government priority on debt recovery and growth now impacted on UK energy innovation spending and strategy. The National Audit Office reported a dramatic decline in total UK public spending after a 2010 high point (NAO, 2013). Increasing concern about the affordability of low carbon technologies was linked by some to a belief that natural gas could continue to have a prominent role in UK energy futures (e.g. Helm, 2012). This carried possible implications for innovation strategy and governance, with calls for reduced focus on innovation for large scale technology deployment, and more emphasis on long term R&D (Moselle & Moore, 2011). By 2013, in a context of reduced political consensus, the role of innovation in energy system change was increasingly contested.

Sustainable Innovation Studies

This section focuses on two prominent strands of sustainable innovation studies: firstly, the Multi Level Perspective (MLP) and Transition Management (TM) (together referred to hereafter as Transitions Studies), and secondly, Technological Innovation Systems (TIS). The focus here on these 'quasi-evolutionary theories' (Suurs & Hekkert, 2012), as opposed to others, such as national innovation systems or innovation management theories, reflects their detailed attention to the socio-technical processes, institutions and interactions involved in innovation and wider socio-technical system change – what Markard, Raven and Truffer (2012: 956) described as their 'systematic view of far-reaching transformation processes of socio-technical systems'. There are now large research literatures on both Transitions Studies and TIS, and this section samples them for points of most relevance, notably on the dynamics of system change and the role of regimes (for fuller overviews, see van den Bergh et al., 2011; Markard et al., 2012; Verbong & Loorbach, 2012).

Transitions Studies

Though described as 'appreciative theory' (Geels, 2002: 1259), in that it draws on concepts and evidence from a number of disciplinary traditions (see Geels, 2004a; Geels & Schot, 2010), Transitions Studies' origins can perhaps be traced most strongly to constructivist social theory (Geels, 2004b), particularly the *social construction of technology* (SCOT) (Pinch & Bijker, 1984).[2] Responding to limited representations of technological change in 'modern' sociology, SCOT translated sociology of science constructivist theory to describe technological change in terms of the varied interpretations and enrolment strategies of different social groups. SCOT's focus on social agency and on the early stages of technology development met with criticism from proponents of more structurally-informed accounts of innovation (e.g. Russell, 1986; Winner, 1993), leading to calls for greater attention to the intermediate *meso* level, where the influence of established organisations and institutions could be analysed, alongside alternative niches (Sørensen & Levold, 1992).

Transitions Studies was conceived to cover this wider socio-technical canvas. It emerged in the Netherlands in the late-1990s, building on a tradition in Dutch innovation studies and research-policy exchange, following-on from approaches such as Constructive Technology Assessment (Rip et al., 1995) and Strategic Niche Management (Kemp et al., 1998).[3] From its beginnings, the Transitions Studies research field has involved co-evolving strands of on the one hand, theoretical and empirical development, often through historical case studies of socio-technical system development (the MLP strand), and on the other hand, research-policy exchange and policy application (the TM strand). A later section reviews the implementation of Transitions Management in Dutch policymaking; the focus here is on conceptual foundations.

Transitions Studies understands sociotechnical change as an outcome of the interaction of three distinct levels of socio-technical structuration: micro-level *niches*, meso-level *regimes* and macro-level *landscapes*. Within this, 'system innovations' (or transitions) – defined as those innovations most influential on system make-up and performance – are understood to originate mainly in niches:

> 'regimes generate incremental innovations, radical innovations are generated in niches … [so] system innovations start in … niches' (Geels, 2004b: 35, 42).

Regimes are defined as the 'dominant rule-sets supported by incumbent social networks … embedded in dominant artifacts and prevailing infrastructures' (Verbong & Loorbach, 2012: 9). Regimes are seen as being 'dynamically stable' (Elzen et al., 2004); for Markard, Raven and Truffer (2012: 957) a regime 'imposes a logic and direction for incremental socio-technical change along established pathways of development'. System innovations are understood as being emergent rather than tightly planned, with lengthy periods of experimentation, learning and network building (Geels & Schot, 2010: 80). This is associated with an iterative, reflexive policy style, aimed at 'bending' innovation dynamics in the direction of policy objectives, rather than imposing more direct control (Elzen et al., 2004). Transitions Studies' niche-led perspective is intertwined with its interest in sustainable innovation: niches provide vital 'incubation spaces' where more sustainable technologies can be created and nurtured (Kemp et al., 1998).

Transitions Studies offered a systematic, intelligible way to frame the complex structures and dynamics of socio-technical change, and in the early-2000s it started to gather increasing attention in academic and policy circles, especially in western Europe. By the mid-2000s, its rising status in sustainable innovation studies started to meet with some critical attention. In one prominent critique, Berkhout, Smith and Stirling (2004) identified a need to challenge the niche-led account, and called for greater attention to the way landscape pressures, such as policy directives, market reforms and public opinion could place direct pressure on regimes – and to regimes' adaptive capacities under such pressures.

Soon after, Geels accepted a 'bias towards novelty' in the MLP (Geels, 2005: 85), and subsequent theoretical contributions have acknowledged that niches alone are incapable of system innovation. Geels and Schot (2007) offered a typology of 'transition pathways' based on different niche-regime-landscape relationships, some of which admit a more proactive role for regime agency: in the *transformation pathway*, new regimes grow out of old ones under moderate landscape pressures; in the *reconfiguration* pathway, incumbents' adoption of components developed in radical niches triggers a subsequent system innovation. Even so, system innovations were still seen as arising in niches, with regimes to be either enrolled or overthrown (Geels & Schot 2007; 2010).

Technological Innovation Systems

Rather than the sociology of technology, the conceptual origins of Technological Innovation Systems (TIS) studies lie more in 'evolutionary economic' theories of technology variation and selection. Evolutionary economics is more attendant to structural aspects of innovation than constructivist sociology – its pioneers introduced the concept of 'technological regimes' (Nelson & Winter, 1982). Even so, evolutionary economics also offers an essentially niche-led account of innovation dynamics, with technology variation and selection operating mainly through firms and markets (Nill & Kemp, 2009).

Over the past two decades evolutionary economics has spawned a number of innovation systems frameworks, focussing variously on nations, sectors, regions and technologies. Within this, *technological* innovation systems framings have a particular orientation to niche-led change. Carlsson and Stankiewicz (1991: 112) distinguished their technological systems analysis from the national innovation systems approach by its 'greater emphasis on microeconomic aspects … than on institutional infrastructure'. Looking back at the development of both national and technological IS approaches in the 1980s and 1990s, Carlsson, Elg and Jacobsson (2010) contrasted the top-down national innovation systems approach (developed by the OECD) with the bottom-up technological systems approach articulated in parts of Swedish academia; they noted rival theories were tools in a 'political struggle over the nature of science and technology policy' (Carlsson et al., 2010: 162).

Weber and Hoogma (1998: 546, emphasis added) contrasted the attention to 'macroscopic' factors in national innovation systems studies with their micro-level technology systems perspective, which involves '*assuming* that new technologies typically become established on the basis of bottom-up processes'. Criticising the perceived failings of national innovation systems analysis for its 'institutional determinism', Hekkert et al. (2007: 414-415) made clear that in developing their TIS framework – which has been influential in academia and policymaking over the past decade – their concern was to 'take the firm, or the entrepreneurial project, as a starting point'.

Two broad phases of development are often identified in TIS Studies: an initial, *formative* phase characterised by the trialling and testing of novel designs, establishing niche markets and building-up societal legitimacy for a new technology; and a subsequent *market expansion* phase, characterised by market growth, learning-by-doing and scale economies (Jacobsson & Bergek, 2004; Jacobsson et al., 2004). Much TIS research has focussed on the formative phase, and TIS theoreticians have stressed the need for long periods of interactive learning and network building in this period. Jacobsson et al. (2004) suggested that 'several decades' of formative phase learning were typically needed, often with little to show by way of deployment over the first few decades; they added that policy support in the formative phase should emphasise 'variety rather than volume' – i.e. small-scale experiments rather than scale economies.

Later versions of TIS theory have analysed innovation dynamics as a group of several interacting system *functions* (e.g. Hekkert et al., 2007; Bergek et al., 2008). This functional framing retains an emphasis on micro-level agency as an engine of system development, especially firm-level entrepreneurship. Positive feedback loops between functions – 'motors of sustainable innovation' – are seen as the mechanism for accelerated innovation system development (Suurs & Hekkert, 2012).

The TIS view of innovation dynamics has been criticised for offering a 'point source' narrative, with the wider world understood mainly as an enabler of (or barrier to) emergent system growth (Geels, 2007; Markard & Truffer, 2008). Nevertheless, and despite some ontological tensions between Transitions Studies and TIS (Geels, 2010) they are seen by some as complementary (Markard & Truffer, 2008) and there have been recent efforts to combine them together (e.g. Meleen & Farla, 2013). According to Suurs and Hekkert (2012: 154) for all 'quasi-evolutionary theories' (strategic niche management, MLP, TM and TIS) 'a transition is regarded as a regime shift … through an accumulation of niches that interact with a destabilizing regime'.

Applying Sustainable Innovation Studies: Research-Policy Exchange

Transitions Management[4]

From its beginnings, Transitions Studies has been concerned to interact with and inform policy; Kuhlman et al. (2010) noted their 'basic assumption' that practice, policy, research and theory formed an interactive, learning 'dance floor' – a metaphor that perhaps best resonates in the Netherlands (Rotmans et al., 2001; Rotmans & Kemp, 2003). From the outset, energy systems were a key domain for testing out Transitions Studies in practice, and there are now a number of 'insider' retrospective accounts of the implementation of Transitions Studies approach in Dutch energy and environmental policy (e.g. Kemp & Rotmans, 2009; van der Loo & Loorbach, 2012), and also reviews from interested 'outsiders' (e.g. Kern & Smith, 2008; Meadowcroft, 2009; Kern, 2011; 2012a).

As these contributions make clear, Transition Management – the strand of Transitions Studies concerned with policy application and research-policy exchange – involved close collaboration between policymakers and researchers. Kern (2011) traced the origins of TM to a small group of researchers, policymakers and consultants with shared 'firm beliefs' on the need for transformational long term changes in socio-technical systems. While there was substantial informal co-operation within this group, business actors were less involved. Although in some ways a radical movement – van der Loo and Loorbach (2012: 220) describe TM as an attempt to 'radically transform a dominant regime', it also resonated with a long-established Dutch 'polder' model of deliberative, consensus-based politics (Kern, 2011).

Initial interest in Transitions Studies among Dutch policymakers reflected perceived shortcomings of earlier environmental policies. TM offered a promising alternative to, on the one hand, more direct planning and control approaches (which were thought too disruptive) and, on the other hand, to the use of economic incentives (which were thought too weak) (Rotmans et al., 2001). However, the appeal of TM also reflected ongoing changes in the institutional context of energy and environmental policymaking in the Netherlands – especially, its promise to allow policymakers to retain influence at a time of Dutch energy sector liberalisation (Kern, 2011). Van der Loo and Loorbach, (2012: 223) noted that TM 'fitted nicely in the ongoing policy debate'.

There are now several studies reporting the limited impact of TM on Dutch energy policy and energy system change. For Kern and Smith (2008), these limitations reflected over-optimism about the prospects of radical change, and the neglect of powerful political and commercial forces. Van der Loo and Loorbach (2012: 221) conceded that over the course of the 2000s, the Dutch Energy Transition Project had 'not …been able to change the dominant energy regime'. They traced these failings to the loss of early radical ambitions as the project became institutionalised, and they concluded that 'the dominant regime appears to slow down the energy transition effort, if not overtly countering it' (van der Loo & Loorbach, 2012: 243). These problems have not been restricted to the Netherlands: Heiskanen et al. (2009) reported TM's sceptical reception and limited impact in Finland, in terms of the 'huge distance … [to] prevailing policy realities', including a high level of conflict on energy policies.

There is no agreement about the implications of the limited impacts of Transition Management within the Transitions Studies community. For some, the lesson drawn is for a changed tactical response: for example, redirected efforts on cities and regions to escape the resistance of incumbent national regimes (Markard et al., 2012). Weber and Rohracher (2012) argued for a blending of Transition Studies' radical, 'transformation-oriented' (but weakly influencing) agenda with the more conventional, 'structurally-oriented' (but more policy-friendly) agenda of TIS.

For others, the implication is for reflection on the conceptual tenets and strategic ambitions of Transitions Studies and TM. Meadowcroft (2009) noted the inescapably complex and contested nature of sustainable energy transitions. One aspect of this complexity is *technological ambiguity*, in that the transformative potential of technologies such as carbon capture and storage – a technology dismissed by some transitions scholars as a short-term technical fix (e.g. Rotmans & Kemp, 2003) – cannot be known in advance. Even if it was possible to categorise CCS unambiguously as an 'incremental' technology, Meadowcroft (2009) added, it may still be judged desirable in a context of urgency and fossil fuels lock-in. Meadowcroft concluded that 'we should probably avoid getting too hung up on 'system change' … our concern should be solving societal problems, not tilting at 'systems'' (Meadowcroft, 2009: 336).

Research-Policy Exchange in the UK

Unlike the Netherlands, there have been few tangible links between UK energy policy and innovation studies over the past two decades. This contrast reflects very different political and institutional settings. In the UK, the re-emergence of public energy policymaking in the early-2000s happened well after the privatisation and liberalisation of the energy industries. As Kern (2012b) has noted, UK recent energy policy interventions have been led by Government and business interests, with only a minor role for academics, and weak analytical capacity within the UK civil service. In the Netherlands, the rise of climate change concerns coincided with energy sector liberalisation, and academic framings such as Transitions Studies offered the promise of a still-important role for public policymakers.

Nevertheless, the gathering policy drivers provided some opportunities for research-policy exchange, and there is evidence that parts of the energy policymaking community in the early 2000s was receptive to (if not prepared to explicitly reference) the radical, niche-led perspective associated with Transitions Studies.[5] This was most manifest in the UK Cabinet Office's Performance and Innovation Unit's *Energy Review* (PIU, 2002). In her insider account Mitchell (2008: 71) suggested that the PIU Review, in its transparency and accountability, 'represented a fundamental move away from the paradigm principles in place in the UK'. MacKerron (2009: 79) also suggested that the policymaking style of the early-2000s was a radical departure from UK technocratic traditions, 'less incremental … [and] more inclusive' (MacKerron, 2009: 83). Soon after, according to Mitchell, resistance to change developed and subsequent policies, including 2003 and 2007 policy statements, 'returned energy policy to … the large scale, few large companies, centralized route' (Mitchell, 2008: 122).

A more centralised and authoritarian policy style had quickly re-emerged. MacKerron (2009: 87) concluded that by the end of the 2000s, faced by trade-off between *urgency of response* and *societal legitimacy*, UK energy policymaking had 'largely abandoned the search for legitimacy'. For Scrace and Watson (2009), the changed style of UK energy policymaking over this period reflected the revised perceptions of policymakers and regime incumbents (large utilities, power equipment suppliers, construction companies, fossil fuel companies and industry associations). Similarly Kern (2012b) noted that powerful vested interests made for an 'technocentric, supply-side' policy style, and he called for 'systematic uncovering of the institutional biases and resistances' involved. Mitchell drew a clear lesson from this experience, in terms of the need to break the institutional 'band of iron' holding the UK energy system together: 'regime change … has to occur if a sustainable energy system is to develop … the current political paradigm … has to be broken' (Mitchell, 2008: 88, 202).

In the Netherlands, the term 'transition' became a shared construct of researchers and policymakers (Kern, 2012b). In the UK, while some transitions terminology entered policy language – most prominently the Government's *Low Carbon Transition Plan* – the substantive focus quickly reverted to large scale technology-based solutions. The Transition Plan, though ambitious in its scale and speed of envisaged change, articulated an essentially non-radical, scaled-up version of system architecture and institutions: 'by 2050 virtually all electricity will need to come from renewable sources, nuclear or fossil fuels where emissions are captured … electricity is likely to be used more extensively for heat and transport, so we will probably need more than today' (HMG, 2009a: 169). It is also focussed on the relatively short term: while the Plan articulated a detailed 'route-map' to 2020, post-2020 change was portrayed essentially as a follow-on problem.

Discussion: Accelerated Energy Innovation and Sustainable Innovation Theory

Recent Debates in Transitions Studies: Transition Dynamics and the Role Of Regimes

The characterisation of transitions as radical and disruptive remains an important theoretical starting-point for many transitions scholars; as van der Vleuten and Högselus (2012: 99) noted, 'despite several studies suggesting regime-internal capacity for change, by far most transition research continues to define and study regimes exclusively as a site of resistance to change'. There are many examples; for Voß, Smith and Grin (2009: 277, 282-3, emphasis added), transition management '*presumes* radical innovation in governance priorities … the radical transformation of socio-technical systems … is considered necessary'. Verbong and Loorbach (2012: 7, 14) agreed that 'radical, structural change is needed to erode the existing deep structure (incumbent regime) of a system and ultimately dismantle it'. This upfront framing carries powerful policy implications; for Voß, Smith and Grin (2009: 284), it means "breeding' and 'growing' sustainable systems from niches'; for Smith, Voß and Grin (2010: 445) it implies the destabilisation of incumbent regimes and the promotion of radical green niches. Turnheim and Geels (2012: 49) agreed that 'destabilisation is a relevant focus for advocates of sustainability transitions'.

Alongside these positions, however, are a number other contributions – some empirical, some conceptual – which describe a more proactive account of regime agency in transition dynamics. Raven (2007) differentiated between *niche accumulation* and *regime hybridisation* dynamics; the latter, in which incumbent firms were 'driving actors', were thought particularly important for infrastructure technologies, given their tight coupling and high entry barriers. Raven added that in some situations novel innovations could be incubated in regimes rather than niches. Konrad et al.'s (2007) study of cross-regime dynamics for prospective transitions led to their questioning any ex-ante presumption of niche-led change: 'we should not presuppose that a regime shift is necessarily the one best way' (Konrad et al., 2007: 1192). Geels (2010; 2011) acknowledged that incumbent agency may go beyond reactionary and defensive responses to niches, conceding that many MLP studies have presented homogeneous, monolithic accounts of regimes, under-attending to their 'internal tensions, disagreements and conflicts of interest' (Geels, 2011: 31). Verbong and Geels (2012: 207–8, 217) noted that:

> early multi-level studies suggested that radical innovations emerge in niches, break through and overthrow the existing regime … this pattern … is less likely in infrastructural systems, like the electricity system … due to the enormous sunk investments and the ongoing and planned activities to expand and reinforce existing grids, it does not seem very likely that the electricity system will change as dramatically as some visionaries want us to believe.

Based on a study of different patterns of energy governance across the European Union, Nilsson (2012: 315) concluded that it was 'an open question whether a low carbon energy transition is really contingent on regime destabilization … given the need for large-scale systems, and investments, many mechanisms of the transition appear facilitated, and even dependent, on the current regime'. Similarly, van der Vleuten and Högselus' (2012: 98) analysis of European energy network operators 'challenge[d] the dominant assumption in early transition research that incumbent regimes resist radical change'. Van der Vleuten and Högselus called for a recalibrated approach to transitions research: 'regime analysis should not *take for granted* the 'conservative' nature of regimes and their resistance to major change … we call for a symmetrical analysis of regime stability and change' (van der Vleuten & Höglesus, 2012: 78, emphasis added).

The Multiform Dynamics of Energy Innovation

The emergence of accelerated innovation in the UK energy system and ongoing debate in sustainable innovation studies on the necessarily disruptive nature of transitions invites consideration of the possibility of continuity-based energy system change. There is some historical evidence that continuity-based, incremental innovation has been a significant driver of energy system change. For example, reviewing US federal government energy innovation efforts, Newell (2011) noted the importance of incremental innovation in several areas, such as resource extraction and processing, internal combustion engine efficiencies, industrial process efficiencies and nuclear power capacity factors. Efforts at breakthrough innovations, such as on synthetic fuels, tended to have much less impact. For Newell, the success of incrementally-oriented innovation programmes derived from their ability to leverage incumbent interests and resources. Similarly, Solomon and Krishna (2011) identified incumbent support (and central planning), as key elements in the resilience and growth of Brazilian sugarcane fuel and French nuclear power programmes. In the UK electricity system, incremental innovation (conversion efficiency improvements and technology substitution & fuel switching) had a significant impact – reducing effective CO_2 emissions by over 36% between 1990 and 2009 (DECC, 2010).

There is also evidence that regime incumbents may be more dynamic than is often presupposed. Christensen's (1997) account of the challenges of disruptive innovation for incumbents has been accused of a selective reading of empirical evidence and for overstating the innovative inertia of incumbents (Danneels, 2004; Macher & Richman, 2004). This is borne out by some historical evidence. In the UK electricity sector, incumbent organisations proved highly responsive to disruptive threats associated with industry privatisation, and transformed their long-established technology strategies in a few months (Winskel, 2002). Bergek et al. (2013) found some incumbents in the automotive and energy sectors capable of driving and absorbing disruptive innovation– challenging received assumptions in the strategic management literature: 'we identify over-optimism regarding new entrants' abilities to disrupt established industries, *partially generated by [management] theories*' (Bergek et al., 2013: 1210, emphasis added).

Other evidence highlighted a range of incumbent strategies to landscape pressures. Stenzel and Frenzel (2008: 2645) found both proactive and defensive responses by utilities to the challenge of renewables development: 'although incumbents are usually seen as being resistant to change … some utilities proactively drove change'; they concluded that co-opting incumbents into the policy process could lead to 'virtuous circles of technology diffusion and capability development' (Stenzel & Frenzel, 2008: 2656). In recent UK debates on electricity market reform, different utilities have aligned themselves with alternative policy support mechanisms, according to their technology assets and strategic interests – such that a UK parliamentary committee observed that 'low-carbon generation must not be viewed as a homogenous category' (HCECC, 2012: 31).

Prescriptions for Accelerated Energy Innovation

As energy system change has become a priority for energy policymakers and strategists, it has attracted the interest of wider sections of the academic community. The result has been a burgeoning number of prescriptions for accelerated system change and energy innovation. A recurring (though often underlying) theme in this debate is the relative merits of different innovation styles (or governance arrangements) innovation. While a number of different terms and typologies have been introduced[6], distinctions can be drawn between advocates of *niche-led* change (dominated by relatively decentralised, emergent, bottom-up and discontinuous dynamics); *regime-led* change (dominated relatively incremental and continuous dynamics); and *breakthrough* change (dominated by centrally co-ordinated, top-down dynamics).

For example, Mowery, Nelson and Martin (2010) advocated an essentially niche-led approach: decentralised, diverse, with long periods of niche-based learning; they concluded that emergent nature of energy system change meant that it was 'difficult if not impossible to plan or predict the structure of the overall R&D effort in any detail' (Mowery et al., 2010: 1020). Others have cautioned against niche-led disruptive change. Unruh (2002) concluded that given deep levels of energy system lock-in, established development pathways, aligned with incumbent corporate and political interests, were likely to offer more effective responses to urgent change imperatives. Similarly, for Hargadon (2010), the high upfront costs and long asset lifetimes of energy technology implied a continuity-based approach: 'eschewing the transformational potential of a technology precisely because its technical artefacts, patterns of production and consumption, experiences, labor etc. exist already may preclude the very attributes that enable rapid scaling and broad adoption' (Hargadon, 2010: 1026). Rather than novelty, Hargadon called for a focus on bottlenecks affecting existing technologies.

However, while he advocated a regime-led continuity-based response, Hargadon (2010) cautioned against centrally-planned breakthrough efforts, citing the historic failings of US energy innovation in this regard. Indeed, while breakthrough metaphors have been prominent in US energy innovation policy efforts (Anadón, 2012) few academic contributors have advocated such a response. In one such contribution, however, Perrow (2010) argued that although decentralised approaches were appropriate for some parts of the energy system (such as energy efficiency) a centralised top-down approach *was* appropriate for large-scale generation technologies such as carbon capture and storage.

Conclusion and Future Research: Accelerated Energy Innovation Studies

This paper has traced the emergence and manifestation of 'accelerated energy innovation' in the UK energy system – and considered its possible implications for sustainable innovation research. Our underlying philosophy – shared with others in the sustainable innovation studies community – is that policy, practice and theory should be seen as co-evolving, interacting domains with aspirations of mutual shaping over time.

In the late-2000s, under urgent drivers for energy system change – decarbonisation, supply security, affordability and business growth – the UK energy innovation system was remade around the 'accelerated innovation' imperative (Table 2). This remaking involved a prominent role for the private sector and for public-private partnerships, to relatively short-term innovation dynamics around deployment and cost reduction, and to the scaling-up or renewal of existing technologies and infrastructures.

Table 2. UK Energy Innovation System Development since 2000.

Period	Economic and Political Context	Institutional Setting	Governance Style
Early-2000s	Benign economic context. Decarbonisation driver emerges, though overall energy system driven by market actors.	Growing but still small innovation spending. Public sector-led small-scale initiatives.	*Niche-based*. Marginal role of innovation in energy system change, focus on long-term transition.
Late-2000s	Benign economic context. Long-term decarbonisation commitment, but growing security and business development drivers.	Rapidly growing public spending. Emphasis on mainstream business-led initiatives and public-private partnerships.	*Shift to continuity-based.* Innovation re-oriented to regime organisations and closer alignment to overall system goals.
Early-2010s	Economic / financial crisis; Statutory commitments on decarbonisation and renewables, but strong cost reduction / growth drivers.	Rapidly fluctuating public spending. Business-led agenda, but reduced policy / political consensus.	Mostly *continuity-based.* Focus on cost reduction for short term policy targets, but uncertain outlook and growing conflict.

The UK provided a dramatic case of energy innovation system remaking, reflecting the hollowed-out institutional base over which accelerated change imperatives exerted their influence. The private sector had a powerful role in this process, with marginal roles for some public bodies – although public-private partnerships have created many recent opportunities for the public energy research community. The manifestation of accelerated energy innovation in other national and international settings – and the extent to which the UK case is highly particular, or illustrative of wider trends – is an important research issue.

The paper also reviewed recent developments in sustainable innovation studies, especially 'quasi-evolutionary' theories. A number of recent contributions here have recognised the prospects of more continuous, incumbent-led dynamics in energy innovation and system change – perhaps reflecting the emergence of accelerated innovation imperatives, and also, the limitations of Transition Management in practice. Our paper was intended as a contribution to this ongoing debate; rather than *advocating* regime-led change, our aim has been to recognise accelerated energy innovation as an important recent phenomenon in the UK, and reflect on its implications for research and research-policy exchange.

As yet, accelerated energy innovation remains more of a policy and strategy phenomenon than a material influence on wider energy system change (in terms, for example of reduced technology cost or accelerated deployment of large scale technologies). Indeed, the technologies identified as major contributors to accelerated system change in the UK – nuclear power, offshore wind and carbon capture and storage – have all recently experienced cost escalations and/or delayed roll-out. While ongoing regulatory changes are aimed at addressing these issues (HMG, 2013), their impact has yet to be seen, and in the meantime the prospects for accelerated innovation are uncertain and contested, with some analysts calling for a reduced coupling between energy innovation strategy and deployment imperatives in the shorter term, and a refocused emphasis on longer term radical innovation. In this context, efforts at regime-led system change may be considered the first phase of a sequence of transition types, with regime-displacing change to follow on under sustained landscape pressures (see Geels & Schot, 2007: 413; Geels & Schot 2010b: 77).

Even under an uncertain outlook, however, the working-out of the accelerated innovation imperative has already seen the wholesale remaking of the institutions, governance and spending patterns of the UK energy innovation system. Organisations manifesting the imperative such as the Energy Technologies Institute and Technology Strategy Board have transformed energy innovation practice in the UK – not just among their private sector interests, but also for much of the public energy researcher base. Accelerated innovation forces have not only driven the remaking of energy innovation policy and strategy – they have reshaped innovation practice, and redefined the role of innovation in wider socio-technical system change.

As such, we have argued, the accelerated energy innovation phenomenon invites critical reflection within sustainable innovation studies, attending to the dissonance between sustainable transition theories and energy innovation policy and practice. For example, within the established Transition Studies' typology, moderate landscape pressures are associated with relatively continuous, regime-led responses, and stronger or more acute pressures with more discontinuous, niche-led changes. In the UK case, however, gradual landscape pressures were relatively accommodating of emergent, niche dynamics, while more acute pressures prompted a shift to continuity-based dynamics. The extent to which regime reinforcement is a characteristic response to urgency is another key research question.

In the wider research literature, alternative styles of energy innovation have been articulated, with differing degrees of emphasis on incremental and disruptive innovations. Some advocate a portfolio of styles, combining short term continuity with long term disruption (e.g. Weiss & Bonvillian, 2009; Lester & Hart, 2012). The social and technical interdependencies of energy systems are likely to present difficulties here, in terms of calls to break-up incumbent interests while rapidly progressing established technologies, while the suggested migration from incremental to radical solutions will encounter new lock-ins created by efforts to meet short term targets. While some of the contributions to these wider debates may lack theoretical underpinnings, or draw questionable analogies with other sectors, they at least suggest a heterogeneity of possible responses to urgent change imperative, and the need further research.

The sustainable innovation studies community has tended to neglect the research agenda associated accelerated energy innovation. In the meantime, other disciplinary perspectives, such as organisational studies, strategic management and risk studies have offered insights, for example, on the relative merits of planned or adaptive management styles (Lenfle, 2011), on energy technology innovation as corporate strategy propositions (Bowen, 2011), and on the socio-technical risk profiles of different energy technologies (Millar & Lessard, 2008). Geels (2011) has recognised the prospective added value for transitions studies from wider disciplinary contributions, and Markard, Raven and Truffer (2012) set out how the field could be 'enriched and challenged' by opening it up to disciplines such as economic geography, political science and the philosophy of science. As well as these wider contributions, there is also prospective value from drawing on neglected strands of innovation studies, such as large technical systems theory (Hughes, 1983; Summerton, 1994; Coutard, 1999).

Sustainable innovation studies has provided many important contributions to knowledge and research-policy exchange: revealing the dynamic interplay of multi-level structures and agents, and the value of diversity and experimentation in early stage innovation. Such contributions – and innovation studies' underlying commitments to reflexive and critical enquiry – have continuing value, especially given the risks and pitfalls of efforts at accelerated innovation. At the same time, however, there is a need to reflect changed drivers, contexts and responses. In striving for co-evolution with policy and practice, sustainable innovation studies should more fully address the multiform dynamics and governance of energy systems under urgency, across a broad spectrum of continuity-based and disruptive change.

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References

Anadón, L. (2012) 'Missions-oriented RD&D institutions in energy between 2000 and 2010: A comparative analysis of China, the United Kingdom, and the United States,' Research Policy 41(10): 1742-1756.

Anadón, L., E. Mielke, H. Lee, M., Bunn & V. Narayanamurti (2010) Transforming the Energy Economy: Options for Accelerating the Commercialization of Advanced Energy Technologies: Framing Statement Energy Technology Innovation Policy (Boston: Harvard Kennedy School).

Bergek, A. & S. Jacobsson (2002) 'The Emergence of a Growth Industry: A Comparative Analysis of the German, Dutch and Swedish Wind Turbine Industries,' in S. Metcalfe & U. Canter, U. (eds), Change, Transformation and Development: Schumpeterian Perspectives (Heidelberg: Physica/Springer): 197-228.

Bergek, A., S. Jacobsson, B. Carlsson, S. Lindmark & A. Rickne (2008) 'Analyzing the functional dynamics of technological innovation systems: A scheme of analysis,' Research Policy 37(3): 407-429.

Bergek, A., C. Berggren, T. Magnusson, M. Hobday (2013) 'Technological discontinuities and the challenge for incumbent firms: Destruction, disruption or creative accumulation,' Research Policy 42(6-7): 1210-1224.

Berkhout, F., A. Smith & A. Stirling (2004) 'Socio-technical regimes and transition contexts,' in B. Elzen, F. Geels & K. Green (eds), System Innovation and the Transition to Sustainability: Theory, Evidence and Policy (Cheltenham: Edward Elgar): 48-75.

BIS (Department of Business, Innovation and Skills) (2009) R&D Scoreboard (London: Department of Business, Innovation and Skills).

Bowen, F. (2011) 'Carbon capture and storage as a corporate technology strategy challenge', Energy Policy 39(5): 2256-2264.

Carlsson, B. & R. Stankiewicz (1991) 'On the nature, function and composition of technological systems', Journal of Evolutionary Economics 1(2): 93-118.

Carlsson, B. Elg, L. & S. Jacobsson (2010) 'Reflections on the Co-evolution of Innovation Theory, Policy and Practice: The Emergence of the Swedish Agency for Innovation Systems', in R. Smits, S. Kuhlmann & P. Shapira (eds), The Theory and Practice of Innovation Policy, (Cheltenham: Edward Elgar): 145-166.

CCC (Committee on Climate Change) (2008) Building a Low-Carbon Economy: The UK's Contribution to Tackling Climate Change (London: TSO).

CEC (Commission of the European Communities) (2009) Directive 2009/28/EC of the European Parliament on the promotion of the use of energy from renewable sources (Brussels: Commission of the European Communities).

Christensen, C. M. (1997) The Innovators' Dilemma : When New Technologies Cause Great Firms to Fail (Boston: Harvard Business School).

Coutard, O. (ed.) (1999) The Governance of Large Technical Systems (London: Routledge).

Danneels, E. (2004) 'Disruptive technology reconsidered: a critique and research agenda', Journal of Product Innovation Management 21(4): 246-258.

DECC (Department of Energy and Climate Change) (2010) Energy Trends: March 2010 (London: National Statistics and DECC).

DECC (2011a) Planning Our Electric Future: A White Paper for Secure, Affordable and Low Carbon Electricity (London: Department of Energy and Climate Change).

DECC (2011b) Overarching National Policy Statement for Energy (EN-1) (London: The Stationery Office).

DTI (Department of Trade and Industry) (2003) Our Energy Future: Creating a Low Carbon Economy (London: Department of Trade and Industry).

DTI (2006) The Energy Challenge: Energy Review (London: Department of Trade and Industry).

DTI (2007) Meeting the Energy Challenge: A White Paper on Energy (London: Department of Trade and Industry).

Elzen, B., F. Geels & K. Green (2004) 'Transitions to sustainability: lessons learned and remaining challenges', in B. Elzen, F. Geels & K. Green (eds), System Innovation and the Transition to Sustainability: Theory, Evidence and Policy (Cheltenham: Edward Elgar): 282-300.

ERP (Energy Research Partnership) (2007) UK Energy Innovation (London: Energy Research Partnership).

ERRG (Energy Research Review Group) (2001) Recommendations to Inform the Performance and Innovation Unit's Energy Policy Review (London: Office of Science and Technology).

Geels, F. (2002) 'Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study', Research Policy 31(8-9): 1257-1274.

Geels, F. (2004a) 'From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory', Research Policy 33(6-7): 897-920.

Geels, F. (2004b) 'Understanding system innovations: a critical literature review and a conceptual synthesis, in B. Elzen, F. Geels & K. Green (eds), System Innovation and the Transition to Sustainability: Theory, Evidence and Policy (Cheltenham: Edward Elgar): 19-47.

Geels F. (2005) Technological Transitions and Systems Innovations (Cheltenham: Edward Elgar).

Geels, F. (2007) 'Feelings of discontent and the promise of middle range theory for STS: Examples from technology dynamics', Science, Technology & Human Values 32(6): 627-651.

Geels, F. (2010) 'Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective', Research Policy 3 (4): 495-510.

Geels, F. (2011) 'The multi-level perspective on sustainability transitions: Responses to seven criticisms', Environmental Innovation and Societal Transitions 1(1): 24-40.

Geels, F. & J. Schot (2007) 'Typology of sociotechnical transition pathways', Research Policy 36 (3): 399-417.

Geels, F. & J. Schot (2010) 'The dynamics of transitions: A sociotechnical perspective', in J. Grin, J. Rotmans & J. Schot, J. (eds), Transitions to Sustainable Development: New Directions in the Study of Long term Transformative Change (New York: Routledge): 9-101.

Gross, R., P. Heptonstall, D. Anderson, T. Green, M. Leach, M. & J. Skea (2006) The Costs and Impacts of Intermittency: An Assessment of The Evidence on the Costs and Impacts of Intermittent Generation on the British Electricity Network (London: UK Energy Research Centre).

Grubb, M., N. Haj-Hasan and D. Newberry (2008) 'Accelerating innovation and strategic deployment in UK electricity: applications to renewable energy', in M. Grubb, T. Jamasb & M. Pollitt (eds), Delivering a low-carbon electricity system: Technologies, Economics and Policy, (Cambridge: Cambridge University Press).

Grubler, A. F. Aguayo, K. Gallagher, M. Hekkert, K. Jiang, K., L. Mytelka, L. Neij, G. Nemet and C. Wilson, C. (2012) 'Policies for the Energy Technology Innovation System (ETIS)', in Global Energy Assessment: Toward a Sustainable Future (Cambridge: Cambridge University Press and Laxenburg, Austria: the International Institute for Applied Systems Analysis): 1665-1743.

Hargadon, A. (2010) 'Technology policy and global warming: Why new innovation models are needed', Research Policy 39(8): 1024-1026.

HCECC (House of Commons Energy and Climate Change Committee) (2012) Electricity Market Reform, Fourth Report of Session 2010-12 (London: House of Commons Energy and Climate Change Committee).

HCSTC (House of Commons Science and Technology Committee) (2006) Meeting UK Energy and Climate Needs: The Role of Carbon Capture and Storage. (London: House of Commons Science and Technology Committee).

Hekkert, M., R. Suurs, S. Negro, S. Kuhlmann & R. Smits (2007) 'Functions of innovation systems: A new approach for analysing technological change', Technological Forecasting and Social Change 74 (4): 413-432.

Heiskanen, E., S. Kivisaari, R. Lovio & P. Mickwitz (2009) 'Designed to travel? Transition Management encounters environmental and innovation policy histories in Finland', Policy Sciences 42(4): 409-427.

Helm, D. (2003) Energy, the State and the Market: British Energy Policy since 1979 (Oxford: Oxford University Press).

Helm, D. (2012) The Carbon Crunch: How we are getting climate change wrong, and how to fix it (New Haven CT: Yale University Press).

Henderson R. & R. Newell (2011) (eds) Accelerating Energy Innovation: Insights from Multiple Sectors (Chicago: Chicago University Press).

HMG (Her Majesty's Government) (2007) Meeting the Energy Challenge: A White Paper on Energy (London: DTI).

HMG (2008) Climate Change Act (Norwich: TSO).

HMG (2009a) The UK Low Carbon Transition Plan: National Strategy for Climate and Energy (Norwich: TSO).

HMG (2009b) The UK Renewable Energy Strategy (Norwich: TSO).

HMG (Her Majesty's Government) (2011a). Implementing the Climate Change Act 2008: The Governments Proposal for Setting the Fourth Carbon Budget (Norwich: TSO).

HMG (2011b) The Carbon Plan: Delivering Our Low Carbon Future (Norwich: TSO).

HMG (2013) Energy Act 2013 (Chapter 32) (Norwich: TSO).

HMT (Her Majesty's Treasury) (2011) National Infrastructure Plan 2011 (Norwich: TSO).

Hughes, T. (1983) Networks of Power: Electrification in Western Society 1880-1930 (Baltimore MD: John Hopkins University Press).

ICEPT (Imperial College Centre for Energy Policy and Technology) (2003) Innovation In Long Term Renewables Options in the UK: Overcoming Barriers and Systems Failures (London: Imperial College).

IEA (International Energy Agency) (2010) Energy Technology Perspectives 2010: Scenarios and Strategies to 2050. International Energy Agency, Paris.

IEA (2011) Good practice policy framework for energy technology RD&D, International Energy Agency, Paris.

IEA (2012) Energy Technology Perspectives 2012: Pathways to a Clean Energy System, International Energy Agency, Paris.

IEA (2013) Energy Technology Research and Development Database (Edition: 2013) (Manchester: University of Manchester).

Jacobsson, S. & A. Bergek (2004) 'Transforming the energy sector: the evolution of technological systems in renewable energy technology', Industrial and Corporate Change 13(5): 815-849.

Jacobsson, S., B. Andersson & L. Bångens (2004) 'Transforming the Energy System: the Evolution of the German Technological System for Solar Cells', Technology Analysis and Strategic Management 16(1): 3-30.

Jacobsson, S. & A. Bergek (2011) 'Innovation system analyses and sustainability transitions: Contributions and suggestions for research', Environmental Innovation and Societal Transitions 1 (1): 41-57.

Kemp, R., J. Schot & R. Hoogma (1998) 'Regime Shifts through processes of niche formation: The approach of strategic niche management', Technology Analysis and Strategic Management 10(2): 175-195.

Kemp, R. & J. Rotmans (2009) 'Transitioning Policy: co-production of a new strategic framework for energy innovation policy the Netherlands', Policy Sciences 42(4): 303-322.

Kern, F. & A. Smith (2008) 'Restructuring energy systems for sustainability? Energy transition policy in the Netherlands', Energy Policy 36(11): 4093-4103.

Kern, F. (2011) 'Ideas, Institutions and Interests: explaining policy divergence in fostering 'system innovations' towards sustainability', Environment and Planning C: Government and Policy 29(6): 1116-1134.

Kern, F. (2012a) 'An International perspective on the Energy Transitions Project', in G. Verbong & D. Loorbach (eds), Governing the Energy Transition: Reality, Illusion or Necessity? (Abingdon: Routledge): 277-295.

Kern, F. (2012b) 'Using the multi-level perspective on socio-technical transitions to assess innovation policy', Technological Forecasting and Social Change 79(2): 298-310.

Konrad, K., B. Truffer, B. & J-P. Voß (2008) 'Multi-regime dynamics in the analysis of sectoral transformation potentials: Evidence from German utility sectors', Journal of Cleaner Production 16(11): 1190-1202.

Kuhlmann, S., P. Shapira & R. Smits (2010) 'Introduction: A Systemic Perspective: The Innovation Policy Dance', in R. Smits, S. Kuhlmann & P. Shapira (eds),The Theory and Practice of Innovation Policy (Cheltenham: Edward Elgar): 1-46.

Lenfle, S. (2011) 'The strategy of parallel approaches in projects with unforeseeable uncertainty: The Manhattan case in retrospect' International Journal of Project Management 29(4): 359-373.

Lester, R. & D. Hart (2012) Unlocking Energy Innovation: How America can build a Low-Cost, Low-Carbon Energy System (Cambridge, MA: MIT Press).

MacKerron, G. (2009) 'Lessons from the UK on Urgency and Legitimacy in Energy Policymaking', in I. Scrase & G. MacKerron (eds), Energy for the Future: A New Agenda (Basingstoke: Palgrave Macmillan): 76-88.

Macher, J. & B. Richman (2004) 'Organisational Responses to Discontinuous Innovation: A Case Study Approach', International Journal of Innovation Management 8(1): 87-114.

Markard, J. & B. Truffer (2008) 'Technology innovation systems and the multi-level perspective: Towards an integrated framework', Research Policy 37(4): 596-615.

Markard, J. R. Raven & B. Truffer (2012) 'Sustainability transitions: An emerging field of research and its prospects', Research Policy 41(6): 955- 967.

Meadowcroft, J. (2009) 'What about the politics? Sustainable development, transition management and long term energy transitions', Policy Sciences 42(4), 323-340.

Meelen, T. & J. Farla (2013) 'Towards an integrated framework for analysing sustainable innovation policy', Technology Analysis & Strategic Management 25(8): 957-97

Millar, R. & D. Lessard (2008) 'Evolving strategy: Risk management and the shaping of mega-projects' in Priemus, in H. Flyvberg, B and van Wee, B (eds), Decision-making on Mega-Projects: Cost Benefit Analysis, Planning and Innovation (Cheltenham: Edward Elgar): 145-172.

Mitchell, C. (2008) The Political Economy of Sustainable Energy (London: Palgrave / Macmillan).

Moselle, B. & S. Moore (2011) Climate Change Policy: Time for Plan B. (London: Policy Exchange).

Mowery, D., R. Nelson & B. Martin (2010) 'Technology policy and global warming: Why new policy models are needed (or why putting new wine in old bottles won't work)', Research Policy 39(8): 1011-1023.

Nelson, R. & S. Winter (1982) An Evolutionary Theory of Economic Change (Cambridge MA: Harvard University Press).

Newell, R. (2011) 'The energy innovation system: a historical perspective', in R. Henderson & R. Newell (eds), Accelerating Energy Innovation: Insights from Multiple Sectors (Chicago: Chicago University Press): 25-47.

Nill, J. & R. Kemp (2009) 'Evolutionary approaches for sustainable innovation policies: From niche to paradigm?', Research Policy 38 (4): 668-680.

Nilsson, M. (2012) 'Energy Governance in the European Union: Enabling Conditions for a Low carbon Transition,' in G. Verbong & D. Loorbach (eds), Governing the Energy Transition: Reality, Illusion or Necessity? (Abingdon: Routledge): 296-316.

Ofgem (Office of Gas and Electricity Markets) (2010a) Project Discovery: Options for Delivering Secure and Sustainable Energy Supplies. Office of Gas and Electricity Markets (London: Ofgem).

Ofgem (2010b) RIIO: a new way to regulate energy networks (Factsheet 93) (London: Ofgem).

Paredis, E. (2011) 'Sustainability Transitions and the Nature of Technology,' Foundations of Science 16 (2-3): 195-225.

PCAST (US President's Council of Advisors on Science and Technology) (2010) Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Federal Energy Policy (Washington DC: PCAST).

Perrow, C. (2010) 'Comment on Mowery, Nelson and Martin,' Research Policy 39(8): 1030-1031.

Pinch, T. J. & W.E. Bijker (1984) 'The social construction of facts and artefacts: Or how the sociology of science and the sociology of technology might benefit each other' Social Studies of Science 14(3): 399-441.

PIU (Performance and Innovation Unit) (2002) The Energy Review (London: Cabinet Office).

Raven, R. (2007) 'Niche accumulation and hybridisation strategies in transition processes towards a sustainable energy system: An assessment of differences and pitfalls,' Energy Policy 35(4): 2390-2400.

Rotmans, J., R. Kemp & M. van Asselt (2001) 'More evolution than revolution: Transition management in public policy,' Foresight 3(1): 15-31.

Rotmans, J. & R. Kemp (2003) Managing Societal Transitions: Dilemmas and Uncertainties: The Dutch energy case-study (Paris: Organisation for Economic Co-operation and Development).

RCEP (Royal Commission on Environmental Pollution) (2000) Energy: The Changing Climate (London: RCEP).

Rip, A., T. Misa & J. Schot (eds) (1995) Managing Technology in Society: The Approach of Constructive Technology Assessment (London: Pinter).

Russell, S. (1986) 'The social construction of artefacts: a response to Pinch and Bijker,' Social Studies of Science 16(2): 331-346.

Scrase, I. & J. Watson (2009) 'CCS in the UK: Squaring coal use with climate change?,' in: J. Meadowcroft J. & O. Langhelle (eds), Caching the Carbon: The Politics and Policy of Carbon Capture and Storage (Cheltenham: Edward Elgar): 158-185.

Skea, J., P. Ekins & M. Winskel (2011) 'UK Energy Policy and Institutions' in J. Skea, P. Ekins and M Winskel (eds) Energy 2050: Making the Transition to a Secure Low-Carbon System (London: Earthscan): 41-66

Smith, A., J.-P. Voß, & J. Grin (2010) 'Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges,' Research Policy 39(4), 435-448.

Solomon, B. D. & K. Krishna (2011) ‚The coming sustainable energy transition: History, strategies, and outlook,' Energy Policy 39(11): 7422-7431.

Stenzel, T. & A. Frenzel (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.

Stern, N. (2007) The Economics of Climate Change: The Stern Review (Cambridge: Cambridge University Press, Cambridge), especially Chapter 14: Accelerating Technological Innovation.

Summerton, J. (ed) (1994) Changing Large Technical Systems (Boulder, CO: Westview Press).

Suurs, R. & M. Hekkert (2012) 'Motors of Sustainable Innovation: Understanding transitions from a technological innovation systems perspective', in G. Verbong & D. Loorbach (eds), Governing the Energy Transition: Reality, Illusion or Necessity? (Abingdon: Routledge): 152-179.

Sørensen, K. & N. Levold (1992) 'Tacit Networks, Heterogeneous Engineers, and Embodied Technology', Science, Technology, and Human Values 17 (1): 13-35.

Turnheim, B. & F. Geels (2012) 'Regime destabilisation as the flipside of energy transitions: Lessons from the history of the British coal industry (1913–1997)', Energy Policy 50 (Special Section, November 2012): 35–49.

TSB (Technology Strategy Board), 2008. Energy Generation and Supply: Key Application Areas 2008–2011(Swindon: Technology Strategy Board).

TSB (Technology Strategy Board) (2011a) Concept to Commercialisation: A Strategy for Business Innovation, 2011-2015 (Swindon: Technology Strategy Board).

TSB (Technology Strategy Board) (2011b) Technology and Innovation Centres: Closing the gap between concept and commercialisation (Swindon: Technology Strategy Board).

Unruh, G.C. (2002) 'Escaping carbon lock-in', Energy Policy 30(4), 317-325.

Unruh, G.C. & J. Carrillo-Hermosilla (2006) 'Globalizing carbon lock-in', Energy Policy 34(10): 1185-1197.

van den Bergh, J. , B. Truffer & G. Kallis (2011) 'Environmental innovation and societal transitions: Introduction and overview' Environmental Innovation and Societal Transitions 1(1): 1-23.

van der Loo, F. & D. Loorbach (2012) 'The Dutch Energy Transition Project (2000-2009)', in G. Verbong, & D. Loorbach (eds), (2012), Governing the Energy Transition: Reality, Illusion or Necessity? (Abingdon: Routledge): 220-250.

van der Vleuten, E. & P. Högselus 'Resisting Change: The transnational dynamics of European energy regimes', in G. Verbong & D. Loorbach (eds), Governing the Energy Transition: Reality, Illusion or Necessity? (Abingdon: Routledge): 75-100

Verbong, G. & F. Geels (2012) 'Future Energy Systems: visions, scenarios and transition pathways', in G. Verbong & D. Loorbach (eds), Governing the Energy Transition: Reality, Illusion or Necessity? (Abingdon: Routledge): 203-219.

Voß, J-P, A. Smith & J. Grin (2009) 'Designing long-term policy: rethinking transition Management', Policy Sciences 42(4): 275-302.

Weber, K. & R. Hoogma (1998) 'Beyond National and Technological Styles of Innovation Diffusion: a dynamic perspective on cases from the energy and transport sectors', Technology Analysis and Strategic Management 10(4): 545-566.

Weber, K. & H. Rohracher (2012) 'Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive 'failures' framework', Research Policy 41(6): 1037-1047.

Weiss, C. & W. Bonvillian (2009) Structuring an Energy Technology Revolution (Cambridge MA: MIT Press).

Winner, L. (1993) 'Social constructivism: opening the black box and finding it empty', Science as Culture 18(3): 427-452.

Winskel, M. (2002) 'When systems are overthrown: the dash for gas in the British electricity supply industry', Social Studies of Science 32(4): 565-599.
Winskel, M., A. McLeod, R. Wallace, R. & R. Williams (2006) 'Energy policy and institutional context: marine energy innovation systems', Science and Public Policy 33(5): 365-376.
Winskel M., G. Anandarajah, J. Skea & B. Jay (2011) 'Accelerating the Development of Energy Supply Technologies: The Role of Research and Innovation', in J. Skea, P. Ekins & M. Winskel (eds), Energy 2050: Making the transition to a secure low carbon energy system (London: Earthscan) 187-218.

Notes

1 The first author was Research Co-ordinator of the UK Energy Research Centre (2009-14); the second author was Head of the Analysis Team at the UK Energy Research Partnership (2008-13); both positions involved regular liaison with UK energy policymakers, researchers and other stakeholders.
2 As Paredis (2011) noted, Transitions Studies retains an essentially constructivist orientation.
3 Schot and Geels (2008: 539) described Strategic Niche Management (a close relation of the MLP) as 'an attempt to import insights from constructivist science and technology studies into evolutionary economics'.
4 The focus in this section is on Transitions Studies / Management, rather than TIS, because of the greater availability of reviews of MLP-TM use in policy. This is not to discount the policy impact of TIS: Suurs and Hekkert (2012) reported that TIS became 'the dominant paradigm in evaluating and steering societal innovation programmes in the Netherlands' (Suurs & Hekkert, 2012: 177).
5 UK policymakers also showed explicit interest in the TIS perspective in this period – most notably in the UK Government's Renewables Innovation Review (ICEPT, 2003; Winskel et al., 2006)
6 Unruh and Carmillo Hermosilla (2006) differentiated between *end-of-pipe* solutions (such as carbon capture and storage), *continuity approaches* (such as large scale renewables adopted in centralised networks); and *discontinuity approaches* (such as network reconfiguration, and 'strategic niche management').

Mark Winskel
Institute of Energy Systems
School of Engineering
University of Edinburgh
EH9 3JL, UK
mark.winskel@ed.ac.uk

Jonathan Radcliffe
School of Electronic
Electrical and Computer Engineering
University of Birmingham
B15 2TT, UK
j.radcliffe@bham.ac.uk