Remaking the UK's energy technology innovation system

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Remaking the UK's energy technology innovation system: From the margins to the mainstream

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HIGHLIGHTS

- Analyses the dramatic recent remaking of the UK energy technology innovation system.
- Identifies three distinct phases of innovation dynamics and governance since 2000.
- The private sector has played a leading role in UKs innovation system rebuilding.
- There has been a broad shift from niche to mainstream, continuity-based innovation.
- The UK system suffers from unstable funding, fragmentation and low transparency.

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ABSTRACT

The UK energy technology innovation system (ETIS) has undergone wholesale remaking in recent years, in terms of its aims, funding and organisation. We analyse this process and distinguish between three phases since 2000: *new beginnings*, *momentum building* and *urgency and review*. Within an international trend to ETIS rebuilding, UK experience has been distinctive: from a low starting base in the early-2000s, to system remaking under a strong decarbonisation policy imperative in the late-2000s, to multiple and contested drivers in the early-2010s. Public funding levels have been erratic, with a rapid increase and a more recent decline. The private business sector has played a leading role in this remaking, and as this influence has grown, the role and style of energy innovation has shifted from long term niches to the shorter term mainstream. The UK ETIS suffers from persistent problems: fragmentation, low transparency and weak links to the research evidence base.

1. Introduction

One prominent feature of contemporary energy policy and research is an emphasis on accelerated technological change for more affordable energy system transition pathways (e.g. Henderson and Newell, 2011; HMG, 2011; IEA, 2012a). The International Energy Agency (IEA) has declared that 'a national strategy … to accelerate the development and adoption of low carbon technologies is the single most important step to address the energy innovation challenge' (IEA, 2012a, p. 117). A number of scenario studies have suggested that meeting ambitious energy and climate change policies can be most affordably realised with significantly higher levels of spending on energy innovation (CCC, 2010a; IEA (International Energy Agency), 2010a). The UK Energy Research Centre suggested that a 'step-change increase' in UK public spending on energy supply technology RD&D (Research, Development and Demonstration) was economically justified (Winskel et al., 2011, p. 215).

Unsurprisingly then, policymakers in the UK and elsewhere have recently sought to remake energy technology innovation systems—systems that were greatly run-down over preceding decades. The UK's recent efforts at remaking its energy technology innovation system (ETIS)—in terms of the main the actors, networks and institutions involved (Carlsson and Stankiewicz, 1991)— are the focus for this paper.

There is a large recent body of conceptual and empirical research on energy technology innovation (e.g. Chiavari and Tam, 2011;

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Wüstenhagen and Wuebker, 2011; Grubler et al., 2012). Many studies have examined the appropriate mix of support policies (e.g. Fri, 2003; Stern, 2007; IEA, 2011a, 2011b). Among more formal innovation systems approaches, framings vary – focussing on, variously, national, regional or technological scales. Foxon and Pearson (2008) suggested that innovation systems studies can be collectively characterised by their systemic, dynamic and non-linear perspective. Technology-focussed innovation systems analysis has been a very active area of research over the past decade, with more recent work tending to adopt an explicitly functionalist analysis of system performance (e.g. Jacobsson and Bergek, 2011; Suurs and Hekkert, 2012). Within this, there have been relatively few studies of the UK ETIS (e.g. Gross, 2004; Foxon and Pearson, 2008; Watson, 2008; IEA 2012b).

A number of authors have derived 'best practice' guidelines for energy innovation policy from the research literature. Among the high-level messages here, Chiavari and Tam (2011) and Grubler et al. (2012) noted the need to position and align innovation policy within overall energy policy objectives; Grubler et al. also called for a systematic approach spanning demand-side technologies as well as supply, and also, sustained support over time rather than 'stop–start' efforts. Winskel et al. (2006) and Foxon and Pearson (2008) highlighted the need for distinctive policies at different innovation stages, with design variety support in early-stage innovation and market creation and domestic industry support in later-stages. Foxon and Pearson (2008) also noted the need to avoid short-term, inflexible and 'incumbent-oriented' policies. Watson (2008) identified a need for 'radical system innovations and not just incremental ones', and he noted that incumbent companies may not be best placed to implement radical innovations.

Watson (2008) also considered UK ETIS developments in the context of Rothwell's typology of organisational modes of innovation: from the highly linear technology-push mode in the 1950s to the networked model in the 1990s (Rothwell, 1994). As Winskel et al. (2006) noted, the networked model of innovation—with its emphasis on distributed agency and learning, and inter-organisational networks and feedbacks—has underpinned much innovation systems research over the past two decades. In UK ETIS case analysed below, by contrast, more directed, linear and incumbent-oriented organisational modes of innovation re-emerged in the late-2000s, reflecting urgent pressures for wider energy system change. The challenge that this (re)linearisation presents to the networked model still prevalent in much wider innovation studies is an interesting issue for further research.

At the end of the paper (in Section 6) we reflect on the UK experience of ETIS system remaking in the light of these high-level best-practice guidelines. However, our main analytical concerns here are descriptive and interpretive, rather than functionalist or prescriptive. While we discuss some implications for policy and research, we do not attempt to benchmark UK developments against an ideal system or optimal set of specific policies. Like Grubler et al. (2012), we see much of the value of an ETIS perspective as identifying patterns and guidelines across different technologies and contexts, rather than more specific prescriptions or hypotheses, and we have avoided a formal, functional analysis. Following Sagar and Holdren (2002, p. 468), our concern is with 'a mapping of the relevant institutions, their energy innovation activities, and the relationships between them'. However, we also *interpret* these changes by reference to the innovation studies literature, in terms of shifting styles of innovation dynamics and governance.

Innovation systems research spans a broad spectrum of interwoven socio-technical practices. While acknowledging this breadth, our unit of analysis here is the Energy Technology Innovation System (ETIS), reflecting our analytical focus on technological innovation rather than more 'purely' regulatory or organisational innovation. We conceive of the ETIS as the set of main actors/organisations, inter-organisational networks and institutions (including market, regulatory and planning rules, and also less formal norms and values) concerned with energy technology innovation. We see the ETIS as being partly-coupled and partly-aligned with the wider energy system, and while our focus is on technology innovation, we also discuss the changing wider energy system and how changing wider system drivers and responses reshaped the role and make-up of the UK ETIS. The wider energy system is seen as an important source of pressures and imperatives on innovation dynamics and governance

Innovation systems are social constructs that reflect particular material, institutional and cultural settings (Hughes, 1983; Anadón, 2012). The rationale and composition of such systems—their aims and expectations within wider socio-technical change, as well as the actors, networks and institutions involved—are themselves fluid and contested. As we discuss in Sections 5 and 6, the remaking of the UK ETIS over the past decade has involved shifting and contested notions of the role of technological innovation in wider energy system change. While the UK is our main focus—reflecting our primary expertise and interests—we also briefly consider wider international patterns of energy technology innovation, common international challenges and UK performance in international context.

UK experience of energy innovation system rebuilding has been a distinctive one, in terms of the very low starting point in the early-2000s, the rapid pace of change from the mid-2000s, and the erratic pattern of public spending. For much of the period covered here, a strong decarbonisation imperative played-out over a highly liberalised and fragmented institutional context. Over the course of its remaking, there was a shift from niche to mainstream and continuity-based innovation, with a leading role for the business sector and public-private partnerships. However, while it reflects a particular mix of international drivers and local context, the UK's experience also exemplifies international concerns to reconcile different energy policy drivers—decarbonisation, affordability, security and business development—and common challenges, such as creating co-ordinated, 'mission-oriented' innovation systems in privatised industry sectors and liberal economies.

The case study presented here is based on quantitative analysis of spending patterns, qualitative analysis of policy and strategy documents, and our own knowledge and experience of working inside the UK's public ETIS over the past 15 years. Our analysis is also informed by recent research on energy innovation governance. In the next Section we trace the changing composition of the UK ETIS since 2000, in terms of its resourcing, strategic objectives and organisational make-up (Section 2); we then consider UK developments in their wider international context (Section 3) and research debates on energy innovation governance (Section 4). Section 5 brings these different elements together to develop a number of discussion points and lines for further research; Section 6 concludes.

2. Remaking the UK energy technology innovation system

2.1. New Beginnings (2000–2004)

Technological innovation was a marginal pursuit in the UK energy system of the early-2000s. From the mid-1980s onwards, market liberalisation and industry privatisation led to a collapse in RD&D efforts; whilst these forces were felt globally, they were experienced particularly strongly in the UK (Helm, 2003). The UK's privatised energy companies had little strategic interest in technological innovation and there was very little public or private investment in energy innovation in the 1990s (Fig. 1; BIS (Department of Business, Innovation and Skills), 2009). One material aspect of this was the closure of much of the UK's public

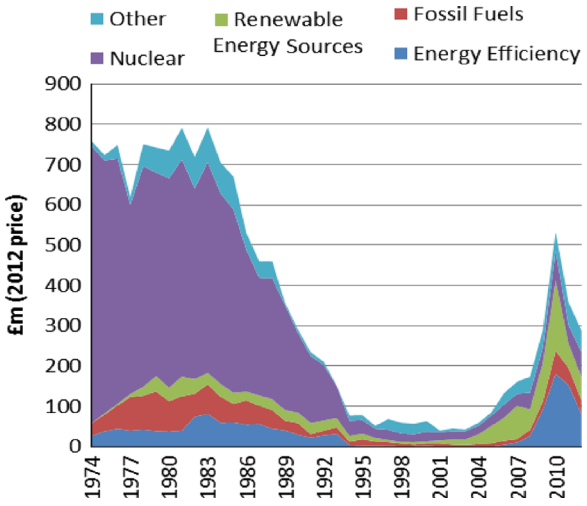

Fig. 1. UK Public Spending on Energy RD&D (1974–2012). (*Source*: IEA, 2013c).

research infrastructure, with remaining skills and facilities dispersed across a small number of isolated research groups.

A number of high-profile reviews and enquiries in the early-2000s paved the way for increased innovation efforts (RCEP (Royal Commission on Environmental Pollution), 2000; ERRG (Energy Research Review Group), 2001; PIU (Performance and Innovation Unit), 2002), but this turn-around started in a very gradual fashion. The principal driver for change was an emerging decarbonisation imperative. The scale of the challenge presented by climate change for energy systems was highlighted by the Royal Commission on Environmental Pollution (RCEP (Royal Commission on Environmental Pollution), 2000). The RCEP concluded that the UK should aim to reduce emissions by 60% on 1990 levels by 2050, implying wholesale changes in the production and use of energy. It also represented a challenge to the technology-neutral principles that had dominated UK energy innovation policy for more than a decade; the RCEP called for stronger market-pull mechanisms for mature technologies and increased early-stage support for those emerging technologies most relevant for the UK.

The actual policy response was limited: spending levels increased only slightly, organisational reforms were modest and there was no major shift from technology-neutrality toward a priority-based innovation system. Nevertheless, energy and climate became prominent issues in policy debate, and in 2001 the Government's Performance and Innovation Unit (PIU) undertook the first systematic energy review since privatisation. On innovation strategy, the PIU was informed by an Energy Research Review Group (ERRG) set up by the Government's Chief Scientific Advisor, a prominent advocate of greater efforts on energy innovation. The ERRG called for UK public spending on RD&D to be raised to bring it in line with that of European competitors (ERRG (Energy Research Review Group), 2001).

The ERRG identified a set of priority technologies for which increased funding could have a significant impact in the UK—including carbon capture and storage (CCS), hydrogen, advanced nuclear, solar PV and marine energy (ERRG (Energy Research Review Group), 2001). This comprised the first technology portfolio for public energy innovation efforts since privatisation, although budgets remained small and more mature technologies, such as wind power, were omitted; instead, technology-neutral market-pull support was to be relied on here.[1] The ERRG also called for greater co-ordination of the UK's re-emerging energy research efforts, and the setting-up of a national energy research centre; the UK Energy Research Centre was duly established as a wholly publicly funded centre, although with a smaller budget than recommended, and as a distributed centre spanning several universities, rather than a single-site national centre.

The Government soon accepted the RCEP's recommended 60% by 2050 target (DTI (Department of Trade and Industry), 2003). Though this re-established the legitimacy of long-term steerage of the energy system, it was modest in terms of its political, economic and institutional impact, at least over political and corporate planning horizons. The carbon emissions of the UK electricity system had fallen steadily during the 1990s and early 2000s (DECC (Department of Energy and Climate Change), 2010) and the Royal Commission and PIU both presented scenarios suggesting that the 60% target could be met largely by a gradual roll-out of renewable energy and energy efficiency measures (RCEP (Royal Commission on Environmental Pollution), 2000; PIU (Performance and Innovation Unit), 2002). Large-scale technologies such as nuclear power and carbon capture and storage (CCS) were *not* seen as central strands of the required response at this time, at least over the short to medium term.

The small amounts of UK public spending on energy innovation in the early-2000s came mainly from the UK Research Councils and central government departments. In a distinctive initiative, the Carbon Trust was established in 2001 as an arms-length publicly funded agency. The Trust's innovation spending equated to a public venture capital fund, focused on business creation for early-stage innovations (Kern, 2011, 2012). Indeed, as Scrase and Watson (2009) noted, the main organisations in the UK ETIS at this time—the Research Councils, Government departments and the Carbon Trust—were all oriented toward niche or long-term innovations. Although a UK system was re-emerging, it remained marginal to the overall dynamics of energy system change.

2.2. *Momentum Building (2005–2009)*

In the second half of the 2000s the drivers of wider energy system change gathered force, providing increased momentum for UK ETIS rebuilding. In a healthy macroeconomic context, there were few concerns about the affordability of energy, or the cost of a more interventionist approach. Indeed, high-level policy targets for change had yet to be translated into interventions of commercial or political consequence, and in the meantime, public spending on RD&D began to increase more significantly (Fig. 2), with a developing interest in the business opportunities of a more interventionist policy approach. At the same time, a confluence of international and domestic forces began to erode the benign conditions for energy: rapidly growing international carbon emissions and fossil fuel investments, stalled progress in domestic emissions reductions and an emerging reliance on imported oil and gas at a time of increasingly volatile international markets (HCSTC (House of Commons Science and Technology Committee), 2006).

While maintaining the 60% decarbonisation commitment, the Government now identified supply security as a key overall policy driver alongside climate change (DTI, 2007). More important roles in wider UK energy system development were suggested for fossil fuels using CCS and new nuclear power stations—implying substantial private sector investment in generation plant and network infrastructure. An emerging policy aim was using public investment to leverage private sector spending, and in a significant departure from technology neutrality principle, the Government now enabled 'banding' of the main renewables deployment

[1] At the same time as the UK's first tentative steps toward innovation system building were being made, the main mechanism for renewables market-pull support was changed from technology-specific contracts to a technology-neutral quota system known as the Renewables Obligation (Mitchell and Connor, 2004).

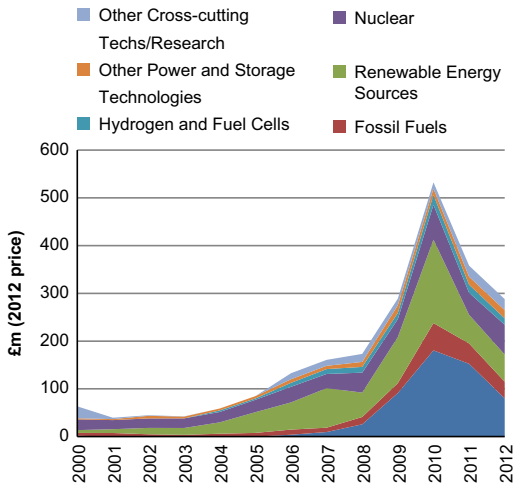

Fig. 2. UK Public Spending on Energy RD&D (2000–2012). (*Source*: IEA, 2013c).

support mechanism to allow greater support for less mature technologies (ibid.).

Within the UK ETIS, more significant institutional changes were now made, with a prominent role for the private sector. The 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 greater emphasis on technology demonstration (ERP (Energy Research Partnership), 2007). In delivering change, there was to be a key role for a new public–private partnership, the Energy Technologies Institute (ETI), which brought significant resources (up to £60 m p.a.) to bridge the gap between R&D and deployment. The ETI built-up its own analytical capability to prioritise its investments. Unlike the (wholly publicly funded) Carbon Trust, this was done largely in confidence to protect the interests of its private funders.[2] The Government defined the ETI′s remit as not only 'to accelerate the deployment of new low carbon energy technologies' but also, to provide a strategic focus the wider low carbon innovation system, including 'direction and pull on the Research Councils' Energy Programme' (DTI, 2007, pp. 224, 225).

In another important development, the UK Government′s Technology Strategy Board (TSB)—a public body with significant private sector representation—now moved from an advisory role to become an executive agency with a significant budget. The TSB′s interests in energy system change focus on business development—its strategic aims are to 'accelerate economic growth by stimulating and supporting business-led innovation' (TSB, 2011), or, in innovation terms, to 'accelerate the journey from concept to commercialisation' (Hannon et al., 2013). Like the ETI, the TSB developed its own funding criteria, prioritising UK industrial capability and global market opportunities; the Board′s early investment priorities included CCS, hydrogen and enhanced oil recovery (TSB (Technology Strategy Board), 2008).

At the end of 2008 the UK′s decarbonisation ambition entered into statute in a Climate Change Act. Reflecting increasing evidence of the possible impacts of climate change, the Act increased the UK′s decarbonisation commitment to 80% by 2050, and broadened the target from CO_2 alone to a basket of six greenhouse gases (HMG, 2008). These revisions implied a significantly more ambitious decarbonisation trajectory—scenarios suggested that the UK electricity system needed to become almost carbon-free by 2030 (CCC (Committee on Climate Change), 2008). Soon after, under a European Renewables Directive (CEC (Commission of the European Communities), 2009), the UK Government agreed to a target of 15% of all energy consumed to be produced by renewables by 2020. Scenarios for complying with the Directive suggested that renewables should provide more than 30% of electricity generated in the UK by 2020 (HMG, 2009b), requiring a hugely accelerated deployment programme.

The Government set out the proposed means for achieving its raised policy ambitions in a *Low Carbon Transition Plan* and *Renewable Energy Strategy* (HMG, 2009a, 2009b); both spelled out the scale and urgency of the technology deployment challenge over the next decade, especially for onshore and offshore wind. After 2020, major supply-side contributions were also anticipated from nuclear power and fossil fuel plant using CCS, and also, an expanded and 'smarter' electricity grid. The Transition Plan outlined a number of reforms to energy innovation strategy: setting key milestones, developing a standard assessment method and mechanisms for improved coordination. To support this, the Energy Research Partnership developed a common vision of technology pathways, timeframes and risks (ERP, 2009) and related innovation milestones (ERP, 2010). The Government stressed the business opportunities all this involved, and the Transition Plan was accompanied by an industrial strategy (HMG, 2009c).

The Carbon Trust now called for a more emphatic move away from technology neutrality towards a technology-focused innovation strategy, with a consistent and transparent prioritisation process spanning 'focussed support' for near-to-market technologies and 'option creation' for longer term prospects (Carbon Trust, 2009). Though such calls were not new, the Trust′s report included detailed techno-economic analysis, sowing the seeds for a series of *Technology Innovation Needs Assessments* (TINAs) produced jointly by the UK public sector energy innovation organisations. Each of the TINAs' provide assessments of a technology′s potential role in the UK energy system, its innovation priorities, the estimated value from cutting costs through innovation, the case for public sector intervention and export opportunities (LCICG (Low Carbon Innovation Co-ordination Group), 2013). By the end of the 2000s, the UK′s efforts on energy innovation were increasingly designed around large-scale technologies and business growth opportunities.

2.3. Urgency and Review (2010–13)

UK efforts on UK energy innovation in the early-2010s were played out in a challenging economic and political context, and a weakening political and policy consensus on energy policy. Decarbonisation and renewables deployment policy commitments were translated into regulations of real commercial and political significance, but wider economic problems and rising fossil fuel prices saw the reassertion of more traditional drivers: affordability, security of supply, and economic growth. This period also saw greater examination of the coherence and effectiveness of the UK′s ETIS, with critical reviews followed by renewed efforts at coordination (CCC; 2010; NAO (National Audit Office), 2010; HCCPA (House of Commons Committee of Public Accounts), 2010; RCUK; 2010; IEA, 2012a, b). After a peak in 2010, public spending on energy RD&D fell back and some organisations now suffered spending cuts.

Energy innovation strategy was now more closely aligned with the wider energy policy agenda, and directed to driving down the costs of the large-scale supply technologies which were seen as the main contributors to system change. The Government set-up cost reduction 'Task Forces' for offshore wind and carbon capture and storage, and articulated a well-defined principle mission for

[2] Whilst the ETI′s analysis is shared with central Government departments—which provide half of its funding—its detailed findings are not made widely accessible.

energy innovation: 'in the 2020s we will run a technology race … before then, our aim is to help a range of technologies bring down their costs so they are ready to compete when the starting gun is fired' (HMG, 2011, p. 1).

Changes to UK energy innovation strategy reflected wider efforts by government to enrol innovation as an engine of economic recovery. An influential report by the Council for Science and Technology concluded that innovation investment in the UK had hitherto lacked 'clear prioritisation, long-term strategic vision' (Hauser, 2010, p. 22), leading to the setting-up of a number of business-focused national Technology and Innovation Centres (later known as Catapult Centres) for key strategic technologies such as renewable energy. Responsibility for Catapult Centre strategy was given to the TSB, and an early priority area for catapult funding was offshore renewable energy technologies, publicly funded at £10 m/yr for 5 years.

As well as this more general drive, a number of critical reviews of the UK ETIS now emerged. The National Audit Office highlighted major weaknesses in UK renewables support: short termism, multiple delivery bodies each with their own objectives and methods, and no arrangements to link individual projects to an overarching plan (NAO (National Audit Office), 2010). Damningly, the NAO concluded that the overall value for money of public support measures for renewables could not be demonstrated. A follow-up report by a UK Parliament Committee (HCCPA (House of Commons Committee of Public Accounts), 2010) concluded that renewables support was delivered through a complex web of organisations, such that the Government lacked a clear understanding of how much had been spent or what had been achieved. The Committee called for new innovation metrics and milestones, regular progress reporting and improved co-ordination. The Committee on Climate Change also highlighted inconsistencies between delivery bodies and Government objectives, and called for stronger links between different stages of the innovation process, improved monitoring frameworks and stronger links to international R&D programmes (CCC, 2010a).

The Research Councils (RCs) now examined the need for a more strategic approach to the rapidly expanding university energy research base (Fig. 3). A RC-commissioned review, conducted by a panel of international experts, though identifying many areas of excellence, identified 'fundamental weaknesses', including a lack of a sustained strategy, competition between different funding bodies, a lack of transparency and 'poorly executed or non-existent mechanisms for moving technologies from the research stages to early demonstration, application and deployment' (RCUK (Research Councils UK), 2010a, p. 1). The review concluded that 'an overarching plan and roadmap … is urgently required' (ibid., p. 43).

The Research Councils' response was to more clearly set out their strategic priorities, including reducing energy consumption and demand, and accelerated deployment of alternative energy technologies. Some areas were now selected for more support (energy efficiency, energy storage and whole systems research) and others for reduction (conventional generation and hydrogen). Demand-side energy research would now occupy a much more prominent position in the portfolio, and a senior Energy Strategy Fellow was appointed to help promote greater coherence across the programme and set out a research roadmap (later 'prospectus') (RCUK, 2012, 2013).

In response to the raft of critical reviews, the Government's Department for Energy and Climate Change (DECC) led a review of low carbon innovation delivery (DECC, 2011a). Co-ordination was to be strengthened through a relaunched and expanded Low Carbon Innovation Co-ordination Group (LCICG)—a strategic forum including the main Government departments and key 'delivery bodies' such as the TSB, ETI and RCs. DECC also committed to producing a low carbon 'technology prospectus' (later a 'strategy review') to show how individual organisational objectives related to one another, and a 'toolbox' of standard appraisal metrics to evaluate innovation programmes.

Some efforts at organisational consolidation of the UK ETIS were now made, with a shift from arms-length bodies to direct Government control, ostensibly in an effort to ensure closer alignment with policy priorities. DECC ended the Carbon Trust's core funding on the grounds of pressure on resources and the desire for enhanced accountability (DECC, 2011b). The Government also abolished the Regional Development Agencies in England, with some of their innovation-related responsibilities instead operated centrally by the Technology Strategy Board.

As the role of some organisations waned, others became more influential. The energy industries' statutory regulator, Ofgem, which had built-up its own analytical capability (Ofgem (Office of Gas and Electricity Markets), 2010), launched a Low Carbon Networks Fund (LCNF), to trial 'smart networks' technology (Ofgem, 2010b). The £500 m Fund represented a step-change on innovation spending by the UK's electricity and gas network operators, and a rebalancing of the overall UK energy innovation landscape towards network infrastructure. Although Ofgem's role

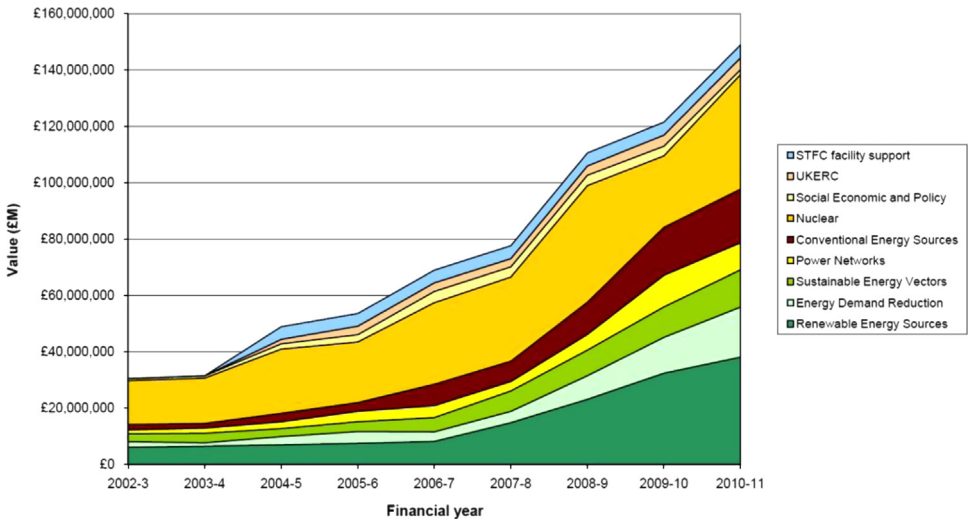

Fig. 3. Research Councils' Energy Programme, Annual Expenditure by Research Theme. *Note* a: the figure is based on published in-year (unadjusted) data. (*Source*: RCUK, 2010a, b).

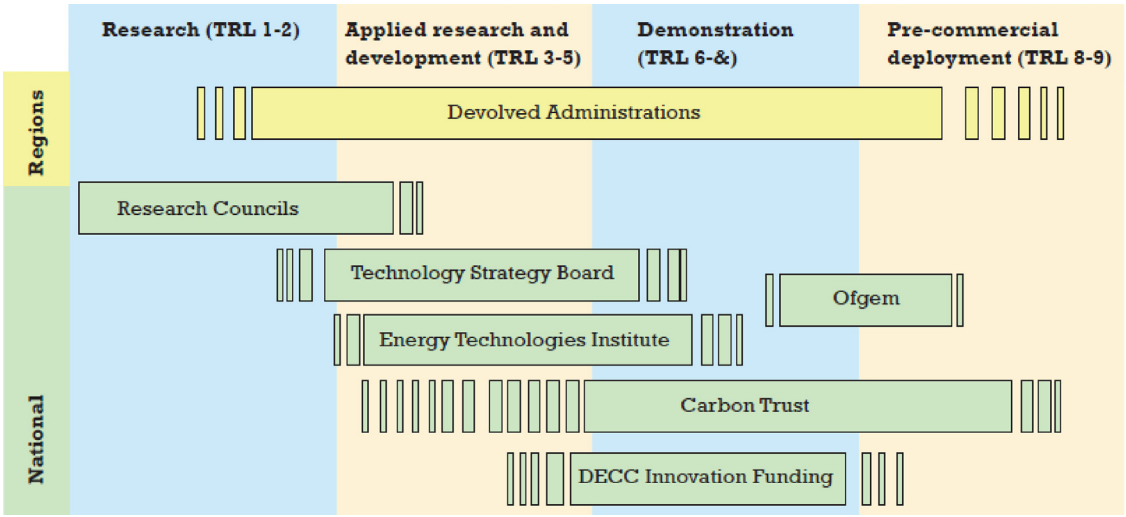

Fig. 4. UK Energy Public Innovation Landscape.
(*Source*: adapted from DECC, 2012a).

Table 1
Main UK public energy innovation organisations.
(*Source*: compiled by authors from multiple sources).

Organisation	Stated mission/role	Priority technology areas (2012)	Nature and scale of innovation funding
Research Councils' Energy Programme (RCEP)	To position the UK to meet its policy targets and goals through high quality research and postgraduate training.	'Growing' research areas include energy efficiency, energy storage, whole systems.	Research grants to UK universities, and eligible research institutions. £110 m p.a. (2011–12)
Technology Strategy Board (TSB)	To stimulate technology-enabled innovation in the areas which offer the greatest scope for UK growth and productivity.	Fuel cells & hydrogen; offshore renewables; grid & digital energy; built environment: low impact buildings; transport; materials	Funding for RD&D projects, to multiple partners, up to £35 m p.a. (2012–13)
Energy Technologies Institute (ETI)	To accelerate the development, demonstration and deployment of a focused portfolio of energy technologies	Offshore renewables; distributed energy; buildings; energy storage and distribution; smart systems and heat; CCS, transport; bio-energy.	ETI receives £60 m p.a. (2008–18) from public and private source for project funding.
Department of Energy and Climate Change (DECC)	To bridge the lengthy gap between a technology being ready and it being widely deployed: the 'valley of death'.	CCS; buildings, offshore renewables; manufacturing	£50 m p.a. from 2011 (£180 m already allocated to priority areas).
Carbon Trust	To tackle climate change by creating a vibrant low carbon economy that delivers jobs and wealth.	Offshore renewables, biofuels and fuel cells.	£10 m p.a. (2010–13) from DECC; support for low carbon entrepreneurs
Ofgem's Low Carbon Networks Fund (LCNF)	To help distribution network operators (DNOs) provide security of supply at value for money as GB moves to a low carbon economy.	Focussed on electricity distribution networks	Project funding through annual competitions up to £100 m p.a. (2010–2015)

is envisaged as focussing on later stage innovation (Fig. 4) its investments have included earlier stage RD&D, posing new co-ordination challenges given the large investment sums involved and the inexperience of many of the bodies involved.

Despite some efforts at greater cohesion, the UK energy innovation public landscape still spanned several arms-length agencies and a number of central Government departments (Fig. 4; Table 1). Each organisation had its own remit and criteria for investment prioritisation, with overlapping responsibilities and interests; devolved administrations in Scotland and Wales and the European Commission had their own arrangements. As the International Energy Agency (IEA) remarked 'the [UK] innovation system lacks clarity and connectivity, with a number of different institutions appearing to cover similar stages' (IEA, 2012a, p. 118). Another report by the IEA, while praising the UK's increased investment and high-level decarbonisation policies, argued that spending levels still did not match policy ambitions, and noted the 'considerable challenge' of distilling multiple initiatives into a comprehensive strategy. Echoing earlier criticisms, the IEA concluded that 'it is not always clear what specific objectives are being pursued … or how effectively the public monies are spent' (IEA, 2012b, p. 160).

The Research Councils' energy strategy fellowship team highlighted the dissonances between different bodies operating at different stages of the UK energy innovation landscape (Fig. 4), in terms of their different timescales, work methods, metrics and incentives (Hannon et al., 2013). The fellowship team noted the rival efforts of different Research Councils, and the 'major gap' between academic research and its commercialisation, with a need for integrated planning methods between business-based and university-based research.

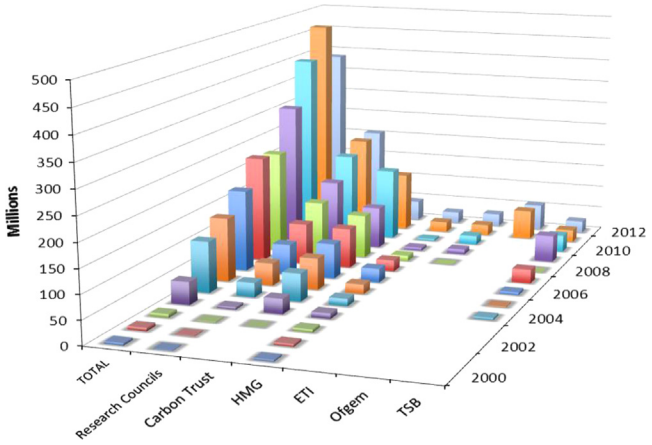

Fig. 5. Reported Spend of Main UK Public Energy Innovation Organisations, 2000–2011. Table Notes: ((a) 'HMG' (Her Majesty's Government) represents total direct UK central government spend across multiple government departments. (b) Fig. 5 is based on published in-year (unadjusted) data; Table 1 is based on estimated/projected annual spending; corresponding data in Fig. 5 and Table 1 may not match).
Source: Compiled by authors from multiple sources include the annual reports and accounts from multiple government departments, Ofgem, and the Carbon Trust; TSB data are taken from the TSB's database at www.innovateuk.org/public-data; data for the Research Councils and ETI are taken from the UKERC Research Register database, at http://ukerc.rl.ac.uk/. Data last updated on 28-05-13.

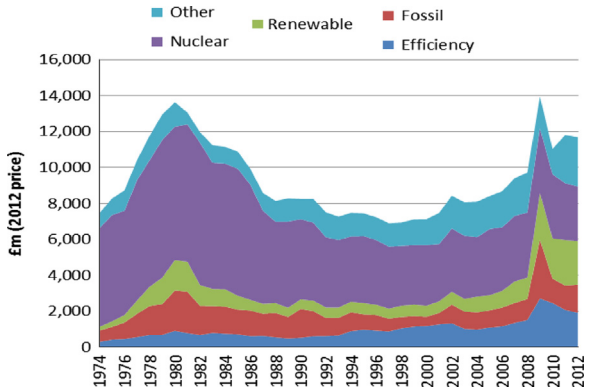

Fig. 6. Energy RD&D public spending in IEA-OECD member countries by technology. (*Source*: IEA, 2013c).

There remained a lack of a long term vision to tie together the UK's energy innovation efforts.[3]

In its 'research prospectus' report, the strategy fellowship team noted that all of the major organisations in the UK energy innovation landscape —including the Research Councils, ETI and TSB—adopted a linear view of energy innovation, manifested through the 'ubiquitous and somewhat casual' use of the 'Technology Readiness Levels' (TRLs) framework (RCUK, 2013, p. 8). The TRL framework, first developed for US military and space programmes, maps technological innovations on a nine-point scale ranging from basic research to pre-commercial deployment. It has been widely adopted by the UK's public sector energy innovation organisations over the past decade, including DECC and the LCICG. At the highest level, it is used to indicate the respective remits of the main organisations in the UK energy innovation landscape (see, for example, Fig. 4).

Fig. 5 traces the changing pattern of energy innovation spending across the main UK public bodies since 2000. Across a changing landscape of multiple organisations and spending programmes, Fig. 4 highlights an overall trend to increased overall spending, but with reduced spend after 2010. Alongside the sustained growth of university-based research through the Research Councils, Fig. 5 suggests an emerging emphasis on applied innovation for deployment support, through the spending programmes of business-oriented or public-private organisations such as the ETI, TSB and Ofgem. More recently this trend has been countered by the loss of funding for the Carbon Trust, leading to a rebalancing of overall effort toward the Research Councils.

In late-2013 the National Audit Office issued an update of its 2010 report, ahead of a parliamentary enquiry on the UK ETIS (NAO, 2013). The report identified some improvements since 2010, with greater co-ordination of technology-specific investments and an improved evidence base, with the publication of the *Technology Innovation Needs Assessments*. At the same time, the NAO found familiar and persistent problems: a lack of overall strategy and shared scenarios, with poor comparability across different technology areas and short-term funding for almost all of the bodies involved. The NAO also confirmed the dramatic decline in total public spending since a 2010 high point – with a one-third reduction in total public spend between 2010–11 and 2011–12 alone.[4] Overall, the NAO concluded that it was 'not yet clear' whether the LCICG's efforts at improved co-ordination had resulted in improved support.

3. International context[5]

3.1. International trends in energy innovation

The UK's dramatic decline in energy innovation spending in the 1980s and 1990s was an extreme case of a wider international trend (Fig. 6; Sagar and Holdren, 2002; Fri, 2003). The need for expanded levels of effort on energy innovation was recognised internationally during the course of the 2000s, and by the start of the 2010s, public spending had reached levels around those seen thirty years earlier (Fig. 6). After a sharp peak in 2009 due to economic recovery programmes, particularly in the US, spending fell back, although still on a rising trend.

National drivers for this resurgence varied greatly, including climate change, energy independence and industrial and economic development. Responses also differed greatly, in terms of institutional and organisational frameworks and the roles of public and private sectors. In the US, for example, public researchers had a leading role in strategy formation (Anadón, 2012). As in the UK, the make-up of international R&D effort has changed significantly: nuclear power claimed only around one third of total spend in 2010 compared to almost three-quarters in 1975, while renewables and efficiency spending both grew considerably.

A striking feature of changing spending patterns has been the increasing importance of the Asia-Pacific region since the mid-1990s, with a corresponding fall in the European share (Fig. 7).[6] Within the OECD, North America accounted for a surge in expenditure since 2008, but otherwise its share has been stable. Fig. 7 separates the UK from the rest of Europe; the UK accounted for as much as 10% of the total

[3] LCICG's review of UK energy innovation strategy is expected to be published in early-2014.

[4] Published evidence on the source of this dramatic decline has yet to emerge, but it appears to reflect inflated levels of capital spending in 2010–11, the removal of the Carbon Trust's core grant after 2011, and the abolition of the Regional Development Agencies.

[5] Only a brief review is possible here, and rather than a comprehensive analysis, our aim is to provide context for the UK case; for more detailed reviews, see Chiavari and Tam (2011), Grubler et al. (2012) and IEA (2012a).

[6] Because these figures exclude non-OECD countries such as China, this shift is more pronounced than the figures show; Grubler et al. (2012) suggested that by the early-2010s the major developing economies were outspending public sector R&D spend among OECD states.

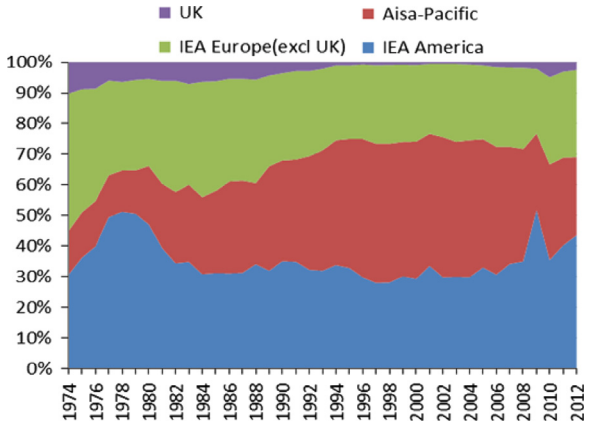

Fig. 7. Proportion of OECD RD&D spend by region. (*Source*: IEA, 2013c).

OECD effort in 1975 but this fell to as low as 0.6% (and only 2% of the European total) in the early 2000s. The UK's recent surge in spending brought it back up to around 5% of the IEA share in 2010—the median level on a spend/GDP basis, but this fell away again with the UK's more recent decline in spending (IEA, 2012b). While the whole of OECD-Europe has had an expanding public innovation base since 2000, the UK change has been a particularly dramatic case of 'stop–start' funding.

3.2. Common challenges

Policymakers face a number of challenges in developing energy technology innovation systems: aligning investment with overall energy policy priorities, striking a balance between basic and applied research, and avoiding fragmentation and duplication of effort. The IEA noted that global investment in RD&D needed to be raised by around 25% by 2020 if policy goals were to be met; beyond 2030, investment would need to be raised by around 50% (IEA, 2012a). Analytical support for budget allocations and the appropriate balance between basic and applied research, though growing, is still limited and the appropriate balance between basic and applied research is difficult to determine (IEA, 2011a). Grubler et al. (2012) highlighted data and information gaps in private sector spending, non-OECD investment, technology spillovers and transfers, and end-use investments.

Budget-setting for more basic energy research remains more of an art than science. The relevant scientists may not regard themselves as energy researchers, and their work may find ultimate application in other fields. For more applied R&D a stronger analytical case for budget-setting may be possible. One approach is to construct energy system scenarios for emerging technologies, such as advanced PV. This provides an approximate insight into the economic benefits that innovation could bring, and a level of funding that might be thought justified. For example, Winskel et al. (2011) concluded that the benefits of accelerating a range of energy technologies in the UK could yield annualised benefits of around £1 bn from 2010 to 2050, roughly twice the actual low carbon innovation spend in 2010 (CCC, 2010).

Another approach to priority-setting is to link spending allocations to declared national technology policy priorities. For countries with well-recognised natural resource endowments or competences (e.g. Brazil/bioenergy; Norway/oil and gas; France/nuclear), the correlations may already be high. For other countries they may be much lower; the IEA placed the UK bottom of a table ranking OECD countries by the proportion of total energy RD&D budgets directed to areas of leading national capability, with only 20% of UK spending directed to technologies where the UK has a leading edge capability (IEA, 2011b).

The problem of duplication and fragmentation of effort is a risk in any country with multiple agencies. One report found that US federal government renewable energy initiatives spanned 23 agencies, 130 sub-agencies and 700 different initiatives (GAO (U.S. Government Accountability Office), 2012). The scope for duplication under such circumstances is unlikely to be in the best public interest. One way to instil greater coherence is to compare the effectiveness of national programmes, and identify synergies between national spending priorities.

3.3. UK international participation

International collaboration on energy innovation promises to reduce the costs of achieving domestic policy targets and help develop export markets. The IEA (2012b, p. 161) noted that for the UK, 'international collaboration… may be essential to accelerate technology development'. In the European Union there have been recent efforts to improve the coherence of research. Spending in the European Commission's "Horizon 2020' programme is embedded in the Strategic Energy Technology Plan (SET-Plan), which elaborates a long-term vision of energy system development. This includes Industrial Initiatives and a European Energy Research Alliance (EERA), comprising 15 leading energy research institutes (UK partner involvement is through the UK Energy Research Centre) to better align national and European sources of funding.

The IEA has also built up a significant range of activities in energy innovation in recent years, through its Implementing Agreements (IAs), and through these, the IEA has become an important forum for co-operation between developed and developing countries (IEA (International Energy Agency), 2010b). The IEA has also become an important analytical source, carrying out in-depth national and international surveys of energy innovation efforts and cross-national studies of good practice (e.g. IEA 2011b, 2012a). The UN has also supported a number of initiatives, such as the Clean Energy Ministerial and the International Renewable Energy Agency (IRENA) (ERP, 2012). More bespoke international collaborations have also emerged in response to specific challenges, such as the International Partnership for Hydrogen and Fuel Cells in the Economy, the Carbon Sequestration Leadership Forum and the Generation IV International Forum for nuclear fission.

Evidence on the effectiveness of UK engagement in international initiatives is mixed. The UK participates in 25 of the IEA's Implementing Agreements, well above the average (ERP, 2012). Within the EU 'Framework 7' Energy Programme (2007–13), UK universities and research organisations have out-performed the European average in attracting support, although the reverse is true for private companies, and for low carbon research (CCC, 2010b). The UK is also perceived as less effective as other states at influencing the design of the Framework Programme for low-carbon technologies (ibid.).

As more consolidated international energy innovation programmes have emerged, the UK's system of distributed centres and has created barriers to participation (ERP, 2012). UK participation in international programmes has been mostly on a bottom-up basis led by individual institutions—often competing—with little overall co-ordination, and the ERP identified a need for stronger linkages between the UK's domestic energy innovation strategy and international engagement (ibid.). The Research Councils' energy review also detected missed opportunities for international collaboration, due to lack of guidelines or incentives (particularly for collaboration outside of the European Union), lack of funding and low awareness or time availability on the part of researchers (RCUK, 2010).

4. Energy innovation governance

This section steps back from the detailed design of innovation policies, programmes and institutions, to consider a broader issue: the governance of an ETIS, in terms of the policies, organisations, networks and institutions that together form an innovation 'style' (Hughes, 1983). We draw here on recent contributions to the innovation studies research literature. Energy innovation is now a mainstream subject among innovation studies researchers, with a burgeoning number of comparative case studies and 'best practice' prescriptions (e.g. Weiss and Bonviliian, 2009; Anadón et al., 2010; Chiavari and Tam, 2011; Henderson and Newell, 2011; Grubler et al., 2012; Anadón, 2012).

While there is broad agreement in this research community on the scale and urgency of the energy innovation challenge, contributors interpret the governance implications of this challenge differently. Many different terms and typologies have been introduced, but to help frame discussion, a distinction is drawn here between contributions advocating three innovation governance styles: (i) *niche*: having an emphasis on relatively decentralised, emergent and bottom-up dynamics; (ii) *mainstream*: having an emphasis on continuity-based and relatively incremental dynamics; and (iii) *breakthrough*: having an emphasis on top-down and centrally planned dynamics.

The breakthrough style of innovation is often seen as having a history of underachievement in the energy sector, and many contributors consider that it remains ill-suited and inappropriate (e.g. Yang and Oppenheimer, 2007; Mowery et al., 2010; AEIC (American Energy Innovation Council), 2011; Nelson, 2011; Lester and Hart, 2012; Foray et al., 2012). Beyond that, however, contributors differ in their objections—and their preferred alternatives. For Mowery et al. (2010), the highly diverse character of energy systems required a decentralised and diverse approach to energy innovation, with long periods of niche-based learning; they concluded that it was 'difficult if not impossible to plan or predict the structure of the overall R&D effort in any detail' (ibid., p. 1020).

Others have cautioned against an emphasis on niche-led disruptive approaches. For Unruh (2002) and Unruh and Carrillo-Hermosilla (2006), the urgency of wider energy challenges requires a focus on mainstream, continuity-led innovation approaches in the short to medium term. Similarly, Hargadon (2010 p. 1026) called for a focus on bottlenecks affecting existing technologies to 'enable rapid scaling and broad adoption'. Though advocating a continuity-led response, Hargadon cautioned against centrally-planned breakthrough efforts, and he highlighted the historic failings of US efforts energy innovation breakthroughs. Lester and Hart (2012, p. 46) argued that the lead times and lock-ins of energy systems implied focussing on more mainstream, continuity approaches. Reviewing US federal government energy innovation efforts, Newell (2011) highlighted the achievements of incremental efforts in areas such as resource extraction and processing, industrial process efficiencies and nuclear power capacity factors. By contrast, breakthrough efforts, such as on synthetic fuels, tended to have much less impact.

Few academic contributors have advocated a breakthrough style. In one such contribution, however, Perrow (2010) suggested that while decentralised, bottom-up approaches to innovation governance were appropriate for 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 (CCS). Though commanding few advocates in the academic research literature, breakthrough approaches have been prominently referenced by politicians (e.g. US White House, 2011). As Anadón (2012) noted, these references have gone beyond rhetoric: recent US energy innovation initiatives, such as ARPA-E and energy innovation hubs, have been designed with explicit reference to the Manhattan Programme.

5. Discussion: remaking the role of energy innovation in the UK

The UK represents a dramatic example of ETIS remaking. In 2013 much of its organisational and institutional make-up was entirely absent a decade earlier. Looking across specific institutional and regulatory developments, and drawing on the innovation studies literature reviewed in Section 4, it becomes possible to interpret the changing pattern of pressures and responses in terms of different energy innovation governance styles. From this perspective, we can deduce a shift from *niche-based* to a mainstream, *continuity-based* innovation in the UK (Table 2).

Embedded UK commitments to market liberalism and technology neutrality, reflected in low levels of energy innovation public investment, planning and co-ordination, persisted into the 2000s, well after the re-emergence of overall energy policy ambitions for change. The need for increased spending and for greater co-ordination was recognised from the outset, but the re-building of the UK system, supported by almost wholly public funds at this stage, was hesitant and at first modest. The risks of fragmentation were acknowledged, but successive governments proved reluctant or unable to undertake wholesale reforms, so that new initiatives were added onto existing measures in layers of increasing complexity, channelled through multiple government departments, organisations and programmes.

Table 2
Phases of UK ETIS development (2000–2013).

Period	Economic and political context	Policy and institutional developments	Innovation dynamics, style and governance
2000–2004 *New Beginnings* (innovation as a niche activity)	Benign context. Decarbonisation driver emerges, but overall system still driven by market efficiency.	Small but growing innovation spending. Mostly public sector led innovation initiatives. Technology-neutral regulation.	Mostly *niche-based*. Marginal role of innovation in overall system change, emphasis on long-term transition. Mostly weak and distributed institutions.
2005–2009 *Momentum Building* (innovation becomes a mainstream concern)	Supportive economic and political context. Decarbonisation-driven change, but growing security and business creation concerns.	Decarbonisation targets entered into statute. Growing RD&D spending, new institutions, with emphasis on public–private partnerships. Shift toward technology-specific regulation.	*Shift from niche- to continuity-based* More central role of innovation in energy system change in short/medium term. Leading role for private sector in remade public innovation strategy.
2010–2013 *Urgency and Review* (contested innovation missions)	Broad focus on debt recovery and growth. Reduced energy policy consensus, with cost of energy concerns becoming dominant.	Policy targets translated into large spending commitments, yet declining RD&D spend after 2010. Criticisms of incoherence, with some efforts at improved co-ordination.	Mostly *continuity-based*. Emphasis on cost reduction and deployment to meet short term policy targets, but growing dispute over wider energy system change and the role of innovation.

In the mid-2000s, in a healthy macroeconomic context, any tensions between sustainability, affordability and security drivers were dormant. Indeed, there was a strong apparent synergy between public (decarbonisation) and private (business development) agendas in the 'momentum building' period, and ETIS rebuilding involved increasingly close public-private relations. Growing overall spending on energy innovation in this period avoided any tensions between longer term and shorter term goals, but much of the new spending was directed toward short-term deployment support and cost reduction: a mainstream, continuity-led approach. The main organisations involved now took a relatively linear view of innovation (RCUK, 2013), and this period saw a shift away from the niche, small firm and network-based model seen in the UK energy system in the early-2000s, and which became prevalent in innovation studies in the 1990s. The re-linearisation of the UK ETIS in the course of its remaking, under pressures for accelerated innovation and urgent wider energy system change, presents an interesting challenge the network model of innovation.

The early 2010s saw intensified efforts on energy innovation, but also a breakdown of economic and political context. The scale and urgency of the wider energy system challenge became clearer, as policy targets were translated into spending programmes and regulatory reforms of real consequence, but this coincided with a deterioration in the overall economy, sowing the seeds for reduced political consensus and a weaker alignment of public-private interests. Public spending was uneven: at first increasing steeply and then falling back sharply, contributing to a turbulent setting for knowledge creation and use.

International differences highlight the importance of political context and institutional history to innovation system design. The UK experience has been a distinctive one: starting from a very low institutional base 'hollowed out' by a long period of market liberalism, followed by a period of rapid remaking. Business interests played a central role in this process, reflecting the relative weakness of the UK public sector, including central government (Kern, 2011). ETIS rebuilding in the UK faced few institutional lock-ins, allowing responsiveness to emerging priorities such as demand-side efficiencies and more mature demonstration stage technologies (Anadón, 2012).

At the same time, a business-led innovation strategy raises some concerns. Incumbent-oriented public-private consortia may focus on near term existing technologies rather than system-transforming innovations (Watson, 2008; Foray et al., 2012). Indeed, the rising influence of business in UK energy innovation strategy has coincided with a shift toward more continuity-based innovation. This said, private capital is likely to have a key role in energy system transformation in many countries, and there is some evidence that under the right circumstances, incumbents can be highly dynamic agents of change (e.g. Bergek et al., 2013). Another concern with business-leadership is reduced transparency in the investment decision-making processes. Private interests will naturally seek to protect their intellectual property and 'know-how', but this should not preclude a level of accountable governance and evidence sharing.

In the early 2010s the UK's fragmented ETIS attracted many critical reviews, leading to efforts at greater cohesion; these efforts are not the first of their kind and it remains to be seen how effective they will prove to be. As overall spending reduced, some arms-length bodies faced cutbacks, with their responsibilities partly absorbed into central government. This presents the risk of political interference, especially at a time of spending pressures and reduced political consensus. A decentralised innovation system is not necessarily dysfunctional, if well co-ordinated. Foray et al. (2012) called for a balance between central control and decentralised agency, with broad priority-setting, co-ordination and progress assessment done centrally, but with an essentially decentralised research programme. The relative merits of centralised versus distributed organisational modes for ETISs is a key research issue.

Reduced political consensus on wider UK energy policy in the early-2010s reflected more austere economic times, and particular concerns on the part of some analysts and politicians about the affordability and desirability of UK energy system transition as set out in the Climate Change Act (HMG, 2008), Low Carbon Transition Plan (HMG, 2009a) and Carbon Plan (HMG, 2011). Opposition to the UK Government's low carbon policies is based on a mixture of arguments: climate scepticism from a small but vocal minority (e.g. Lawson, 2008); concerns about the affordability of support for low carbon technologies and a related belief that natural gas (possibly including shale gas) could offer a cheaper 'lower carbon' alternative to renewables in the medium-term (e.g. Lewis, 2011; Helm, 2012; Less and Newey, 2012). By the end of 2012, uncertainties about the role of gas in UK energy futures were evident within government (DECC, 2012b).

While it has yet to manifest as any major policy revisions, this political dissensus carries implications for UK energy innovation strategy, and may provoke a new style of UK ETIS governance. For example, Moselle and Moore (2011) called for greater emphasis on long term R&D and learning-by-research for globally-relevant technologies such as CCS and PV, and reduced focus on learning-by-deployment and more domestically-oriented priorities such as offshore wind; this has echoes of the niche-based, less directed style seen in the UK in the early-2000s. Already, reduced overall funding has meant greater reliance on the earlier stage innovation efforts of the Research Councils in the UK's energy innovation landscape (NAO, 2013). The counter-argument here is that without sufficiently strong learning-by-deployment support mechanisms, a learning-by-research approach will fail to deliver technology cost reductions and wider system impact (e.g. AEIC (American Energy Innovation Council), 2011; Gross et al., 2012). This debate exposes important differences of view on the role of technological innovation in energy system change.

6. Conclusions

Faced with the global challenge of energy system change—and the role, within this, of energy technology innovation—national responses reflect particular drivers, resources and contexts. There can be no universal blueprint for energy technology innovation system governance, and more prescriptive efforts to identify optimal arrangements are likely to be frustrated; they may also be misplaced: the IEA (2011b, p. 18) noted, confidence in an overall policy support package for technology development and deployment matters more than the choice between specific instruments. Nevertheless, there is now a substantial 'what works' research base on energy innovation, and the high-level guidelines here include: a coherent system-wide perspective, sustained funding over time, avoiding public policy 'capture' by incumbent interests, and supporting a combination of incremental and discontinuous innovations.

Judged against these high-level guidelines, UK energy technology innovation system rebuilding —though impressive in the speed and scale of its transformation—has fallen short in a number of ways. The UK system has been remade in piecemeal fashion, often only weakly coupled to overall policy ambitions; public spending levels have been erratic, organisational fragmentation persists, and the interweaving of public and private interests has at times lacked transparency and accountability. As technology innovation became more tightly coupled to short-term policy ambitions, its role in wider system change was redefined away from long-term niches to the shorter-term mainstream. Though

reflecting international drivers and challenges, UK experience has been deeply shaped by local traditions, interests and exigencies.

Tensions and pressures in the UK energy system have recently intensified, with the prospect of another recasting of the role of innovation in wider system change. Even more than in the benign times that formed the backdrop for much of the rebuilding process reviewed here, this invites research on innovation design and governance. There is a growing international energy innovation research base on national responses to global pressures – yet in the UK, policy-research links remain underdeveloped in this area. Given the uncertain and contested role of technological innovation in the wider energy transition challenge, the need is for stronger references to the evidence base, and more transparent analysis of the choices and trade-offs involved.

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