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Socio-technical Transitions in UK Electricity: Part 1 – History, Actors and Pathways

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ABSTRACT

A large interdisciplinary consortium of engineers, social scientists and policy analysts have developed three low carbon, more electric transition pathways for the United Kingdom (UK): described as ‘*Market Rules*’ (MR), ‘*Central Co-ordination*’ (CC) and ‘*Thousand Flowers*’ (TF) respectively. It adapts an approach based on earlier work on understanding transitions, using a multi-level perspective with landscape, regime and niche levels, and its application to the development of ‘socio-technical scenarios’. These pathways to 2050 focus on the power sector, including the potential for increasing use of low carbon electricity for heating and transport. Part 1 describes studies of historical energy and infrastructure transitions are described that help the understanding of the dynamics and timing of past transitions. The role of large-scale and small-scale ‘actors’ in the electricity sector and the methods used to develop the pathways are then described. In Part 2 associated technologies are evaluated in order to determine the choices that need to be made by UK energy policymakers and stakeholders. There all three pathways have also been appraised in terms of their environmental performance using complementary life-cycle assessment and footprinting methods. Lessons can clearly be drawn for other industrialised nations attempting to decarbonise their electricity generation systems, although local circumstances will determine the country- and region-specific options.

KEYWORDS: Energy; Climate change; Business

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1. Introduction

1.1 Background: The Energy Sector and Climate Change Challenge

Human development is underpinned by energy sources of various kinds that heat, power and transport its citizens in their everyday life (Smil, 2017). But, while energy supplies and technologies underscore continued economic development, they also give rise to unwanted side-effects. Arguably the principal environmental burden emanating from the energy sector is the prospect of global warming due to an enhanced *greenhouse effect* induced by fossil fuel burning (Hammond, 2000; IPCC, 2013, 2019). Carbon dioxide (CO₂) is the principal ‘greenhouse gas’ (GHG) having an atmospheric residence time of about 100 years (Hammond, 2000). This mainly arises from the combustion of fossil fuels [such as coal, natural gas and oil (petroleum)] in power stations and transport, as well as for heating in buildings and industrial processes. Changes in atmospheric concentrations of GHGs affect the energy balance of the global climate system. Human activities have led to dramatic increases since 1950 in atmospheric CO₂; concentrations have risen from 330 ppm in 1975 (IPCC, 2013) to about 408 ppm in 2018 (WMO, 2019). The recent (2013) scientific assessment by the *Intergovernmental Panel on Climate Change* (IPCC) asserts that it is ‘extremely likely’ that humans are the dominant influence on the observed global warming since the mid-20th Century. The 2015 *Paris Agreement* on climate change aims to keep temperatures “well below 2°C above preindustrial levels and to pursue efforts to limit the temperature increase to 1.5°C above preindustrial levels” (Ares & Hirst, 2015). However, *bottom-up* national pledges received in connection with the Paris Conference for GHG mitigation efforts are expected to result in a warming of around 2.7°C, even if fully implemented (Ares & Hirst, 2015). So the world still faces a significant test of reducing GHG emissions further in order to bring global warming into line with the aspirations in the *Paris Agreement*. Indeed, the IPCC in their recent ‘special report’ on the implications of keeping temperatures down to 1.5°C (IPCC, 2019) argued that humanity has just 12 years to respond to the climate change challenge (i.e., by about 2030 rather than 2050 presently incorporated in international agreements), if it wishes to keep global warming to 1.5°C above pre-industrial levels. Thus, it needs to instigate appropriate actions in the very near future.

The evolution of modern industrialised society has been interwoven with discoveries of sources and uses of energy (Hammond & Pearson, 2017), especially the exploitation of fossil fuel resource stocks, the assembly of energy infrastructures, and the development of end-use technologies and practices. With its coal reserves, ports and engineering skills, Britain lay at the heart of the first industrial revolution (Allen, 2009; Wrigley, 2010). Nowadays, while energy supplies underpin continued economic development, this fossil fuel dependence exposes the UK to major risks: supply and resource insecurities; increasing costs of energy supply; and damage to the quality and longer-term viability of the biosphere. The British Government therefore introduced a bold, legally binding aim of reducing the nation’s ‘targeted GHG emissions’ overall by 80% by 2050 in comparison to a 1990 baseline (DECC, 2011) in their 2008 *Climate Change Act* (Climate Change Act, 2008). This initiative led the way globally, and subsequent pathways for achieving such levels of GHG savings are now known

as “deep decarbonisation” in much of the industrialised world (see, for example, Spencer *et al.*, 2017).

The 2°C global warming target agreed at the *Paris Agreement* (Ares & Hirst, 2015) is broadly consistent with the 2050 UK GHG emissions target. It led the British Government’s independent *Committee on Climate Change* (CCC), established under the 2008 *Climate Change Act*, to advocate deep cuts in power sector operational emissions through the 2020s (CCC, 2015), with UK electricity generation being largely decarbonised by 2030-2040. In recommending the *Fifth ‘Carbon Budget’* for the period 2028-2032, they proposed a 57% fall in GHG emissions overall below 1990 levels by 2032. Achieving these CO₂ reduction targets will require a challenging transition in Britain’s systems for producing, delivering and using energy that is not only low carbon, but also secure and affordable; thus resolving three components of the so-called energy policy ‘*trilemma*’ (Hammond & Pearson, 2017). Such GHG reductions will necessitate a rapid transition towards an energy system that delivers high quality energy services through low-carbon technologies and processes, that are also secure and at competitive prices.

In 2018 the UK Government asked the CCC to give it advice on the possible tightening of the 2050 target in light of the *Paris Agreement* (Ares and Hirst, 2015). Its subsequent report advocated a new emissions target for the UK: net-zero GHGs by 2050, i.e., balancing emissions with CO₂ removal. The CCC argued that this target is “achievable with known technologies, alongside improvements in people’s lives, and within the expected economic cost that Parliament accepted when it legislated the existing 2050 target for an 80% reduction from 1990” (CCC, 2019). They also advised that the steepest reductions in GHG emissions must occur before 2030. The CCC suggested that the readily available options include low-carbon electricity [from nuclear power and renewable energy sources {bioenergy, solar *photovoltaic* (PV) arrays, and wind turbines}, which would need to quadruple by 2050], energy efficient buildings with low-carbon heating (required throughout the UK’s building stock, both new and existing structures), electric vehicles (which they view as the only proven light vehicle option by about 2035), developing *carbon capture and storage* (CCS) technology and low-carbon hydrogen (which the CCC regard as necessities not just options). In addition, the CCC propose phasing-out potent fluorinated gases, increasing tree planting, adopting measures to reduce GHG emissions on farms, and stopping biodegradable waste going to landfill. Such policies should together deliver tangible GHG emissions reductions, whereas the CCC viewed current UK climate change policy as being insufficient to meet even the existing 2050 targets (CCC, 2019), i.e., an 80% reduction against the 1990 baseline. The *Climate Change Act* was subsequently amended by the UK Government in June 2019 in order to target a reduction of all GHG emissions to net zero by 2050.

Electricity demand in the UK as a share of overall energy consumption is likely to rise over the longer-term, because it is readily controllable at the point of use and its production can be decarbonised via nuclear and *renewable energy technologies* (RET). The evolution of electricity generation systems since the time of Thomas Edison (1847–1931) has been based around the concept of employing large, centralised power stations. Thus, until recently, the bulk of electricity in Britain was generated by large thermal power plants that were connected to a high-voltage transmission grid, and then distributed to end-users via regional low-voltage

distribution networks. Such a centralised model has delivered economies of scale and reliability, but there are significant drawbacks. It is represented schematically in Fig. 1 (Hammond, 2000), where the role of the electricity network is illustrated. This power generation was resourced from some 39% natural gas, 33% RET (wind turbines, solar photovoltaic cells, hydropower and bioenergy), 18% nuclear power, and 5% coal in 2018 the most recent full year data available at the time of writing in the annual *Digest of United Kingdom Energy Statistics* [DUKES] (BEIS, 2019)). Consequently, the UK *Electricity Supply Industry* (ESI) is still nearly 50% dependent on primary fossil fuels, i.e., natural gas and coal. Heat is lost or energy ‘wasted’ at each stage of system from extraction of primary resources to end-uses that meet demand (Hammond, 2000). Much of the electricity grid was constructed in the 1950s and 1960s. It is therefore heavily reinforced in former coal-mining areas, and is nearing the end of its design life. It restricts the power flow from Scotland to England (2.2GW_e), and via the interconnectors (in the form of high-voltage undersea cables) to France, Northern Ireland and the Netherlands. The grid will therefore require not only renewal, but also reconfiguration of both hardware and software in order to accommodate the introduction of greater levels of distributed generation in the future within the home or on a community- scale.

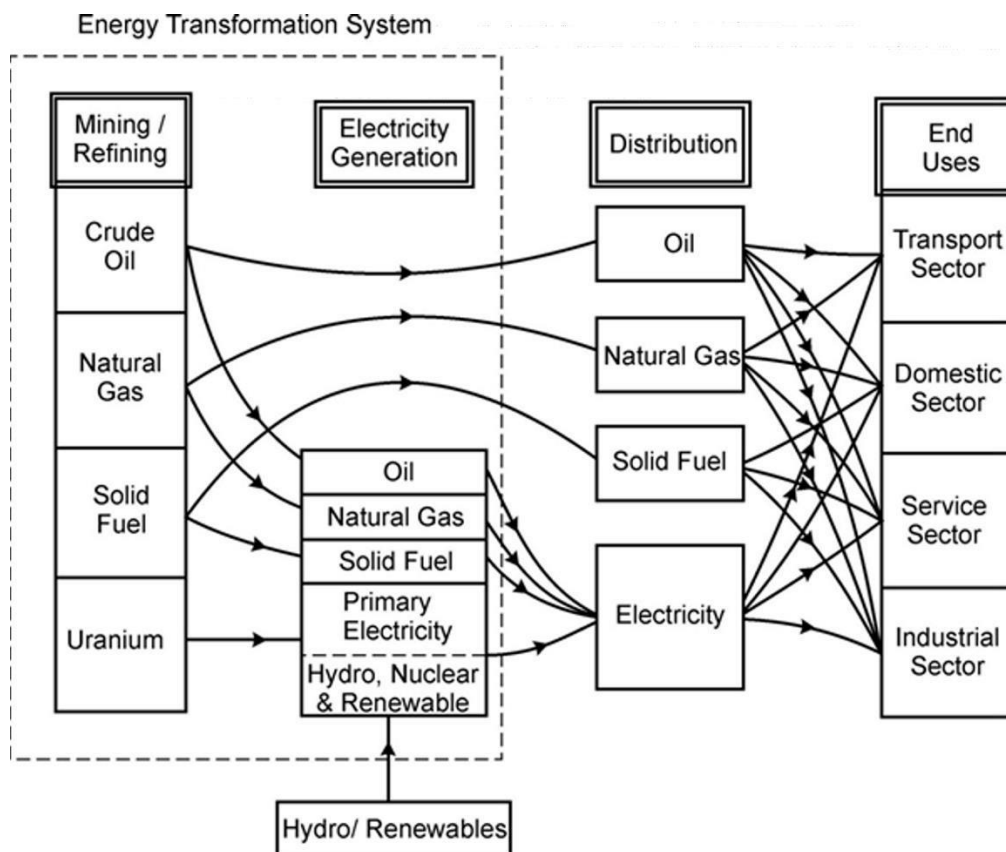


Fig. 1. Simplified representation of the UK energy system. [Source: Hammond, 2000.]

1.2 *The Transitions Approach*

Dutch researchers have pioneered research on transitions in socio-technical systems, which has expanded, diversified and deepened during the last decade, under the broad heading of ‘sustainability transitions’ (Markard *et al.* 2012; Kohler *et al.* 2019). It has influenced their national policy on promoting energy system transitions (Kemp *et al.*, 2007; Kern and Smith, 2008; Verbong and Geels, 2010; MEA, 2005), and stimulated historical case studies (Kemp *et al.*, 2011), including applications to the Dutch electricity system (Verbong and Geels, 2007; Kwakkel and Yücel, 2014). Other analyses have examined transitions from sailing ships to steam ships (Geels, 2002); from horse-drawn to automobile transport systems (Geels, 2005); from cesspools to sewer systems (Geels, 2006); and biogas development in Denmark (Geels and Raven, 2006). It has been used to examine the dynamic interaction of technological and social factors at different levels (Elzen *et al.*, 2004; Geels, 2005), and has generated significant international policy and research interest (Kemp, 1994; Geels, 2002; Voß *et al.*, 2009; Foxon *et al.*, 2010; Markard *et al.*, 2012; Foxon, 2013; Hammond and Pearson, 2013; Hammond and Pearson, 2017; Chilvers *et al.*, 2017). This analytical approach is typically coupled with a *multilevel perspective* (MLP) for analysing socio-technical transitions, based on co-development at and between three levels (Kemp, 1994; Geels, 2002): *niche innovations*, *socio-technical regimes*, and *macro-landscape pressures* [see, for example, Fig. 2 (Foxon *et al.*, 2010)]. The *landscape* represents the broader political, social and cultural values and institutions that form the deep structural relationships of a society and only change slowly (Chilvers *et al.*, 2017). The *socio-technical regime* reflects the prevailing set of routines or practices used by ‘actors’: those involved with the design, implementation operation and use of a particular technological system or network (see, for example, Rip and Kemp, 1998; de Bruijn and Herder, 2009). Whilst the existing *regime* is thought of as generating incremental innovation, radical innovations are generated in *niches* (Kemp, 1994; Geels, 2002). The latter are ‘protected’ spaces that are at least partially insulated from normal market selection in the regime. *Niches* provide places for learning processes to occur, and space to build up the social networks that support innovations, such as supply chains and user-producer relationships.

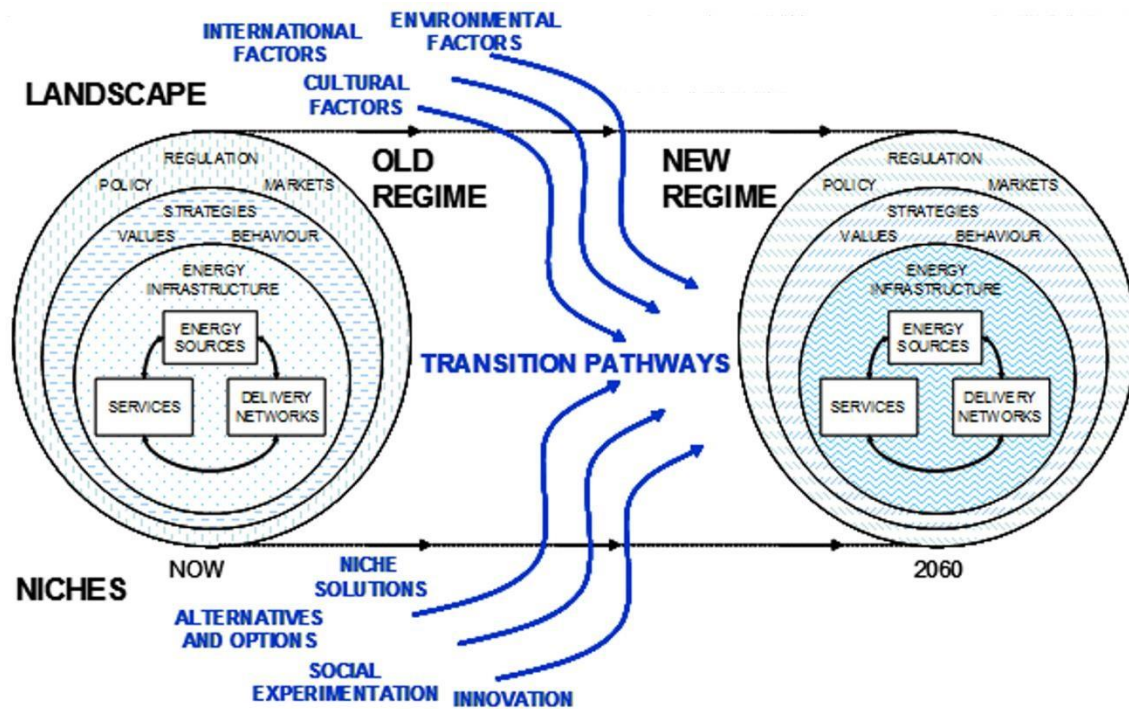


Fig. 2. Possible transition pathways and the factors that influence them.

[Source: The Transition Pathways Consortium (Foxon *et al.*, 2010).]

The transitions approach has been used as a basis for developing ‘transition management’. This is a process of governance seeking to steer or modulate the dynamics of transitions through interactive, iterative processes between networks of stakeholders. It involves creating shared visions and goals, mobilizing change through transition experiments, as well as the evaluation of the relative success of these experiments (Kemp and Rotmans, 2005; Loorbach, 2007; Loorbach *et al.*, 2015). Transition management is thus a form of participatory policy-making based on complex systems thinking. However, the transitions theory or socio-technical approach is not without its critics (Geels and Schot, 2007; Geels, 2010; Geels, 2011; Grubler, 2012; Barton *et al.*, 2018). Although Shove and Walker (2007) recognised the value of ‘sustainable transitions management’ for stimulating change towards predefined beneficial goals, they argued that analyses based on the MLP typically have an over-simplified view of the social realm, being rooted in ‘innovation studies’ (see, for example, Smith *et al.*, 2010). In a response, Rotmans and Kemp (2008) noted that it is an approach that has been used in the Netherlands in particular (see also Kemp *et al.*, 2007; Verbong and Geels, 2007; Kern and Smith, 2008; Verbong and Geels, 2010; Kwakkel and Yücel, 2014; MEA, 2015) to aid the achievement of better futures. Transitions management helps secure incremental system improvements and innovations within the planning framework; often in the face of complexity and uncertainty. Indeed, Grubler (2012) drew on ‘real world’, historical energy transitions in order to highlight the long duration of transitions (many decades) and their slow rates of change, the importance of energy end-uses as drivers of change, and the distinctive patterns needed for the scale-up of technological solutions. But even Grubler (2012) provided cautionary tales. He suggested that low carbon transitions require persistence and continuity of policies, their alignment (e.g., regarding fossil fuel subsidies), and balanced innovation portfolios (e.g., public sector R&D investment and niche market incentives). Geels and Schot

(2007) developed a more detailed typology of transition pathways, focused on refinements to the MLP, in response to critiques and insights in the academic literature (Shove and Walker, 2007; Rotmans and Kemp, 2008; Smith, 2009; Meadowcroft, 2009) that were followed-up by Geels (2010, 2011, 2019). Although many successful transition paths reflect a sequence of events (Geels and Schot, 2007), they are not automatic or deterministic. Many of the pathways may not, in reality, turn out to have a pure format (Geels and Schot, 2007; Geels, 2010; Geels, 2011), and shifts between them can result in those exhibiting mixed characteristics (Geels *et al.*, 2016).

An initial theoretical analysis of past and possible future decarbonisation pathways for the UK (Shackley and Green, 2005) showed the potential for the application of the transitions approach in Britain. Shackley and Green (2005) identified a number of key socio-technical factors that would influence future pathways in terms of policy drivers for change. A number of studies have applied the MLP for a comparative analysis of low carbon electricity transitions in, for example, Germany, the Netherlands and the UK (Laes *et al.*, 2014; Geels *et al.*, 2016). These countries were selected as exemplars of the deployment of RET (Laes *et al.*, 2014), of a transition management framework (MEA, 2005; Kemp *et al.*, 2007; Verbong and Geels, 2007; Kern and Smith, 2008), and of legislative commitment to climate change mitigation (Climate Change Act, 2008) respectively. They identified best governance practices, e.g., creating communities of interest, target setting to link long-term strategies with shorter-term (energy or carbon) budgets, and the adoption of policy incentives. Geels *et al.* (2016) built on the revised typology of Geels and Schot (2007) in their comparison of Germany and the UK electricity transitions. They observed that the dominant transition pathway in Germany was based largely on technological substitution enacted by new entrants who have led the deployment of smallscale RET (Laes *et al.*, 2014). In contrast, incumbent ‘actors’ (such as the *Big Six* electricity utilities) led the deployment of large-scale RET in the UK; mainly onshore, and more recently offshore, wind farms. However, the British policy incentives for RET have been significantly weakened over the last decade (Barton *et al.*, 2018), although Geels *et al.* (2016) believe it is likely that the UK will still meet its current renewable electricity target of 30% by 2020 under the *European Union* agreement. Market conditions have led to a share of electricity generation from RET being 33% in 2018, according to DUKES (BEIS, 2019). Likewise, the take-up of new nuclear power stations and CCS facilities coupled to fossil-fuelled power stations and industrial process plants have been significantly delayed in comparison with what was initially envisaged in the early 2010s (Cooper and Hammond, 2018). The delay by the UK government in publishing an update to its origin *Carbon Plan* (DECC, 2011) may reflect the challenges in ensuring that the UK remains on track for further emissions reductions in the late 2020s and early 2030s (Barton *et al.*, 2018). This plan subsequently became *The Clean Growth Strategy* (HM Government, 2017), and links a low carbon transition to an updated national industrial strategy (Busch *et al.*, 2018; Cooper and Hammond, 2018).

1.3 The Issues Considered

A large interdisciplinary consortium of engineers, social scientists and policy analysts have developed three low carbon transition pathways for a more electric future in the UK out to

2050: termed ‘*Market Rules*’ (MR), ‘*Central Co-ordination*’ (CC) and ‘*Thousand Flowers*’ (TF) respectively. [This large consortium of nine university partners was originally funded via the strategic partnership between *e.on UK* (the electricity generator) and the UK *Engineering and Physical Sciences Research Council* (EPSRC) to study the role of electricity within the context of ‘*Transition Pathways to a Low Carbon Economy*’ (2008-12), and then renewed with funding solely from the EPSRC under the title ‘*Realising Transition Pathways: Whole Systems Analysis for a UK More Electric Low Carbon Energy Future*’ (RTP) (2012-16).] The present research examined the most recent *version 2.1* (v2.1) of the pathway narratives (Hammond and Pearson, 2017; Chilvers *et al.*, 2017; Barton *et al.*, 2018): driven by the market (MR), central government intervention (CC), and civil society (TF) (e.g., local communities and nongovernmental organisations [NGOs]) initiatives: see Table 1. This emphasis on ‘governance’ as a prime mover of market development is a novel feature in terms of energy futures research in Britain (Foxon *et al.*, 2010; Hammond and Pearson, 2013; Chilvers *et al.*, 2017). [The TF pathway’s name was loosely inspired by the late Chairman Mao Zedong’s 1957 invitation to Communist Party cadres in China to criticise the political system then in place within the country: “Let a *hundred* flowers blossom” {often misquoted as the bottom-up injunction to “Let a *thousand* flowers bloom” (Chilvers *et al.*, 2017)}.] This transition pathways research has focused on the choices and actions needed to *get there from here*, and on the analysis of the pathways’ technical, socio-economic and environmental implications. It built on an approach based on earlier work on understanding transitions, as discussed in the previous section. These ‘socio-technical scenarios’ or transition pathways focus on power generation, including the potential for increasing use of low-carbon electricity for heating and transport. The extent to which choices need to be made by UK energy policymakers and stakeholders between the large-scale and small-scale *actors*, pathways and associated technologies are discussed.

Table 1. Key characteristics of the UK *transition pathways*.

Pathway Designation	Market Rules (MR)	Central Co-ordination (CC)	Thousand Flowers (TF)
Governance logic	<i>Market</i>	<i>Government</i>	<i>Civil society</i>
Critical technologies	Fossil fuel (coal and gas) CCS; Nuclear power; Offshore wind	Fossil fuel (coal and gas) CCS; Nuclear power; Offshore wind	Solar <i>photovoltaic</i> (PV) arrays; Onshore & offshore wind; renewable <i>Combined Heat & Power</i> (CHP)
Important trends	Limited interference in market arrangements; high level policy targets and high carbon price.	Central government commission tranches of low-carbon generation from big companies to reduce risk of low carbon investment.	Local, bottom-up diverse solutions led by local communities and NGOs, greater community ownership and more engagement of end-user.
Electricity demand	Increase demand for heating and transport. Overall demand in 2050 (512 TWh) much greater than today.	Increase demand for heating and transport, but reduced through energy efficiency. Overall demand in 2050 (410 TWh) slightly higher than today.	Overall demand in 2050 (310 TWh) lower than today. Higher rate of energy efficiency improvements and more aware consumers.

Source: Chilver *et al.*, 2017; adapted from Foxon (2013).

The present research programme sought to understand and contribute to potential future transitions of UK energy systems and to enhance policy thinking and decision-making. Here (in Part 1) studies of historical energy and infrastructure transitions - which inform how the broad, long-term sweep of change that arises out of interactions between *actors* or *actor networks*, institutions and infrastructures - have helped understand the dynamics and timing of transitions (Chilvers *et al.*, 2017; Pearson, 2018). The *multi-level perspective* (MLP) – encompassing, as noted above, *macro-landscape pressures*, *socio-technical regimes* and *niche innovations* - has been used as the basis for developing the socio-technical scenarios (as depicted in Fig. 2), which can be employed to explore the potential future development of

socio-technical systems through interactions between ongoing processes at the three levels (Elzen *et al.*, 2004; Foxon, 2013; Hammond and Pearson, 2013; Hammond and Pearson, 2017).

In Part 2 all three pathways (MR, CC and TF) are evaluated in terms of their environmental performance using complementary *life cycle assessment* (LCA) and footprinting methods. The energy analysis and environmental LCAs reported by Hammond *et al.* (2013) and Hammond and O’Grady (2014; 2017a; 2017b), evaluated v1.1 and v2.1 of the pathways respectively. *Environmental footprint analysis* (EFA) are also employed to estimate the environmental and resource burdens associated with UK power generation based on historic data and the three transition pathways (Hammond *et al.*, 2019).

2. The UK Energy Sector – The Role of ‘Actors’ Large and Small

The ‘governance’ of energy systems involves choices made by different actors within the sector, such as national and local policy-makers, large firms and new entrants, financial investors and end-users, that give rise to changes to the system (Smith, 2009). These *actors* have a range of individual and social goals, including the supply, provision and use of energy services at reasonable costs, maintaining security of supply, and contributing to wider social and environmental aims, which may often be conflicting – but are sometimes harmonious - in any particular decision process. Institutional arrangements frame the way that these conflicts are resolved, or synergies reinforced, and so strongly influence the governance of energy systems. Furthermore, they interact with present and expected future changes in technologies, such changes create new opportunities and challenge existing arrangements (having new information about the risks of climate change), and with new institutional arrangements and governance processes that create incentives for development of, and investment in, particular technologies and their uses.

The current UK energy regime for meeting lighting, heating and power-related services may be characterized as a centralised system [see DUKES (BEIS, 2019)]. Electricity is generated centrally, largely from fossil fuels (now mainly natural gas), nuclear power and a growing, set of renewable resources (i.e., RET). Natural gas is extracted from the North Sea or imported via pipelines or as *liquefied natural gas* (LNG). It is delivered to homes and businesses through the transmission and distribution networks, before being used to provide end-use services, together with *distributed energy resources* (DER), i.e., small-scale units of local generation connected to the grid at the distribution level, and the building infrastructure. Natural gas is also delivered through a transmission and distribution network, and used to provide heating and cooking services with the aid of end-use technologies and the buildings infrastructure. The markets for the provision of electricity and gas were liberalized in the late 1980s and 1990s in order to facilitate competition between electricity generators, and between companies supplying electricity and gas to homes and businesses, overseen by a regulator *Ofgem*, with the aim of reducing the costs of generating and supplying energy to users. The strategic importance of energy for enabling wellbeing and economic activity means that the system is the subject of intense policy activity, focussed on ensuring continuing, affordable supplies, and meeting other social and environmental objectives, including climate change and global heating.

Key processes at the *landscape* level (see Fig. 2) influencing and ‘driving’ the energy *regime* include: (a) public awareness of climate change and willingness to accept and undertake changes in response; (b) government commitments to meet national and international targets for emissions reductions and promotion of low carbon energy sources; (c) ideological commitments to liberalized energy markets; (d) concerns over security of primary energy supplies (including external factors leading to high oil and gas prices); and (e) factors which could lead to physical disruption of external supplies (war, terrorism, foreign governments limiting supply, etc.). The dominant processes are focused on the energy policy *trilemma*: government commitment to national and international targets for moving to a low carbon energy system, concerns over security of supply, and issues of affordability, competitiveness, and fuel poverty. The UK has signed up to, and was one of the drivers of, the European energy and climate policy back in 2007. This set targets for 2020 of a 20% reduction in European CO₂ emissions, a 20% increase in energy efficiency, and 20% of final energy to come from RET. Such *landscape*-level commitments contained in both national and European energy and climate policy targets need to be translated into direct pressures on the energy regime through enhanced policies and measures.

Another driver of UK energy policy at the *landscape* level is concerns over security of primary energy supplies. A variety of factors anticipated between now and 2030 have led to a perceived generation ‘gap’ and concerns about availability of primary energy sources to enable this supply deficit to be filled, whilst achieving carbon reduction targets. This policy arena has been strongly driven by lobbying from *actors*, including large incumbent utility companies within the existing regime seeking to maintain the current centralized generation system and their role in it. An interesting potential institutional innovation was a proposal to sell energy services rather than units of energy, which was encouraged under the British Government’s *Carbon Emission Reduction Target* (CERT) scheme that operated over 2008-2013. This required energy suppliers to stimulate take-up of low carbon and energy efficient measures by their customers. This type of scheme could potentially lead over the long-term to significant changes in business strategies for large industry players, particularly if they face challenges from new entrepreneurial energy service companies. How these different pressures affect business strategies depends partly on the way in which firms perceive the various commercial risks within the energy system. A survey of a range of stakeholders identified the major risks associated with a rapidly changing UK electricity sector as being: reliance on insecure sources of primary fuels for electricity generation; lack of investment in new infrastructure; decommissioning of nuclear plant leading to reduced capacity; severe weather conditions arising from climate change; and maintenance of capacity margins (Hammond and Waldron, 2008).

The potential exists for a move away from a largely centralised electricity systems towards more decentralised ones (Barton *et al.*, 2018). Whilst many different alternatives exist within each of these routes, they are significantly different from each other, particularly in terms of infrastructures, institutions, and patterns of behaviour. These can be characterised as follows:-

(1) *Centralised generation systems:* Concerns over security of supply, and doubts about the potential to scale up local decentralized technologies, may reinforce strategies of large

energy companies to maintain portfolios of large-scale technologies, including natural gas and nuclear power plants. Hence, investment focuses on these technologies, alongside scale-up of offshore wind, and reinforcement and enhancement of existing transmission infrastructure. The way that targets for emissions reductions and renewable energy sourcing are institutionalized could allow investment by UK companies overseas to count towards UK targets, and so UK domestic targets would become less stringent, delaying early action on decentralized options, and reducing the overall pace of change. This investment in centralised technologies, and associated infrastructure, might crowd out the potential for large investments in decentralized options.

(2) ***Decentralized or distributed generation systems:*** Technical, social and economic concerns relating to the main centralized options, including *carbon capture and storage* (CCS), nuclear power and offshore wind, may lead to greater, renewed interest in decentralised options. Strong local leadership and sharing of knowledge between entrepreneurial local authorities could be reinforced by advocacy coalitions of small-scale *actors*: technology developers, installers and new *energy service companies* (ESCo) promoting decentralised generation (DG). Infrastructure investment might focus on enhancing capacity of distribution networks to actively manage two-way power flows and on investment in the built infrastructure to utilise DER and capture natural energy flows, e.g., through passive solar design and natural ventilation.

3. Past, Present and Prospective Energy Transitions

Studies of historical energy and infrastructure transitions have helped understand the dynamics and timing of transitions (see, for example, Wilson and Grubler, 2011; Sovacool and Geels, 2016; Pearson, 2018). Policy makers tend to have little institutional memory of what has worked or has not worked in terms of energy sector interventions, because job changes are used to enable UK civil servants to gain experience and avoid accumulating positional or departmental loyalty, and because ministers often serve for short periods (Chilvers *et al.*, 2017): from 2008-2015 of the four UK *Secretaries of State for Energy and Climate Change*, one served for less than two years and another for just over one year. Historical analyses/stories of past transitions therefore help them (and other stakeholders) to understand how and why transitions have previously succeeded or failed. They also indicate how long they can take to implement and the reasons why. However, Pearson (2018) recently noted the growing policy focus on ‘low-carbon transitions’, which address the threat of climate change by seeking transitions away from GHG-emitting fossil fuels, towards low-carbon renewable and/or nuclear power. He explored three areas in which further historical analysis could be especially valuable: (i) research into the duration and speed of past energy system transitions and the insights to be gained from their analysis; (ii) path dependence, lock-in and the strategies, responses and destabilisation of incumbent energy actors and institutions; and (iii) theoretical and empirical approaches to ‘sustainability transitions’ and innovation. While most attention has been paid to transition successes, belated attention is now being paid to transition failures and resistance to change by incumbent firms, as well as their fuels, technologies and institutions (Chilvers *et al.*, 2017). Historical case studies also help illustrate the possibility of radical or rapid transformation; and raise questions about the received wisdom regarding past

successes/failures of socio-technical transitions, policies and technologies. The value of historical case studies as analogues lies not in their perfect fit with modern technologies or circumstances (which is unlikely), but in being similar in one or more aspects and yielding insights from the analysis of such similarities and differences.

The historical studies have shown that rapid change is possible, but not necessarily frequent. It may require both a recognition of the need to change, openness to experiment, and a high degree of co-ordination (e.g., the natural gas transition). These studies illustrate how coconstructed are the material or physical aspects with the social, political and institutional aspects. For example, the successful 1966-77 conversion from town gas to North Sea natural gas (under the management of the nationalised *British Gas Corporation*) required both technical changes, including building the national gas grid and installing new burners in millions of gas appliances, along with major institutional reorganisation, new workforce training and political support (Arapostathis *et al.*, 2014; Arapostathis *et al.*, 2019). Pearson and Arapostathis (2017) explored seven transitions in the UK gas industry since its inception in 1805. This paper and that of Arapostathis *et al.* (2019), which focused on the conversion of gas-using appliances, questions whether the current UK gas industry is as well situated to adjust to the low-carbon transition, particularly the heat transition, as the industry of the 1960s was to the transition from town gas to natural gas. They also identify and explore the challenges faced by government in helping to steer this transition.

The subsequent privatisation and liberalisation of the gas market after 1987 led to major structural change and a system regulated by *Ofgem*, with a *Uniform Network Code* (UNC) overseen by the *Joint Office of Gas Transporters*. Vertical integration was aided by new control and communication technologies, together with internationalisation via gas interconnectors. That reduced uncertainties, but increased the system's complexity. This case study (Arapostathis *et al.*, 2014) provided an analogue for the challenges of integrating large, infrastructural technical systems for a sustainability transition. It is inscribed within the MLP approach yet concentrates on system integration as a complex and uncertain socio-technical process. Consequently, it indicates how quite dramatic changes in the UK natural gas structure are mirrored in *regime* formation (see again Fig. 2).

Historical studies of two alternatives to petrol in the inter-war period (Johnson *et al.*, 2016) show how and why emerging technological substitutes can founder and potential transitions fail in times of economic instability, shifting governance and competition between incumbents and newcomers. This study compared transition experiences and *branching points* (i.e., points at which key regime actors felt the need to take decisions to stay on or depart from an existing pathway) of emerging alternative liquid fuels in Britain during previous recession and growth periods between the First and Second World Wars (WWI and WWII), i.e., 1918-1938. The case studies focussed on alcohol fuel produced by the *Distillers Company Ltd.* (DCL) for power generation and a petrol-from-coal produced by *Imperial Chemical Industries* (ICI). Both fuels received government support during a time of rapid growth in the motor industry, fluctuating economic conditions and fears of absolute oil shortages. They represent examples of failed attempts at path creation and transition. Nevertheless, the studies identified the importance of network infrastructure, ownership of this infrastructure, and the impact of energy security on prevailing governance framings or 'logics'. Thus, Johnson *et al.* (2016) observed that when

energy is seen as ‘insecure’, it tends to be framed as a social service (or article of warlike material) rather than a commodity, with growing political legitimacy of policy interventions. They found that crude oil market instability, support for a declining coal industry, and militaristic needs all motivated the search for these alternative liquid fuels in the inter-war period. Governance of fuel distribution had significant effects on the economic feasibility of both fuels and their ability to penetrate a market dominated by the oil industry incumbents. Changing characteristics of energy security influenced the framing of energy and shifts in government support for alternative transport fuels. Lack of state regulation of incumbent oil company *cartels* and access to fuel distribution infrastructure impeded emergence of these new fuels. This analysis of failed attempts at path creation (Johnson *et al.*, 2016) can therefore usefully inform understanding of current energy governance and low carbon transitions.

There is relatively little historical work on demand reduction. However, the recent study of the *Electricity Development Association* (EDA) and domestic electric heating in early post-war Britain (Carlsson-Hyslop, 2016; Chilvers *et al.*, 2017) suggests that the electricity industry’s attempts at persuading consumers to reduce demand illustrate some of the challenges facing demand reduction today. The EDA, originally established as a public relations arm of the UK electricity industry, tried simultaneously to reduce undesirable peak demand, whilst encouraging increased demand more generally. In the late 1940s it recommended that electric fires should not be used to meet peak demand. However, in the 1950s and 1960s the EDA, focusing on the growing market for central space heating, concentrated on promoting off-peak heating appliances. It first sought to do this in the UK via under-floor heating, and then *block storage heaters* typically composed of clay bricks or other ceramic material. The study analysed the way in which the then *London County Council* (LCC) and its tenants adopted, adapted to and in some cases resisted the use of electric underfloor heating. It concluded that attempts at promoting demand reduction by the electricity industry during the period 1945-1964 had only a limited effect on the trend towards rising energy end-use demand. This was, in part, due to the EDA’s promotional efforts and conflicting objectives.

The recent review of historical energy studies by Pearson (2018) noted several problem areas, including the distinction between the many kinds of ‘minor’ and ‘major’ (or ‘grand’) transitions. He observed that the ability of historians to draw such distinctions with confidence has implications for their - and our - capacity to comprehend the scale, pace, duration, smoothness and (dis)continuity or other ‘special’ properties of particular transitions. Such comprehension is however limited, as is its ability to offer insights into how to guide or manage them. Pearson (2018) argued, nevertheless, that historical analyses can offer insights into past energy transitions that are of value to non-historians who study past, current and prospective energy transitions and, where appropriate, to policy-makers who seek to grapple with them. He also noted the ambiguity, even contradiction in the literature, and suggested that greater clarity would be valuable (Pearson, 2018). Finally, he extended an invitation to interested historians to further share the methods, subtleties and findings of historical analysis with non-historians, to enhance our knowledge, understanding and thinking about energy transitions.

4. The Low Carbon, More Electric UK Transition Pathways

4.1 Visions of Low Carbon, More Electric UK Futures

Several studies have been undertaken in recent years that yield low or zero carbon energy scenario sets for the UK [see, for example, the three UK pathway/scenario sets discussed by Allen and Hammond (2019)]. The focus of the present study is on the three pathways developed by the *Transition Pathways Consortium* (see Section 1.3). It consisted of UK engineers, social scientists, policy analysts, and innovation specialists (and included the present authors). As noted, this Consortium sought to develop and explore ‘transition pathways’ towards a UK low carbon electricity system (Foxon *et al.*, 2010; Chilvers *et al.*, 2017), to understand the changing roles of large and small *actors* in the dynamics of these transitions, and to learn from the successes and failures of past transitions. The research team have focused on the choices and actions needed to “get there from here”, and on the analysis of technical, socio-economic and environmental implications of the pathways (Foxon, 2013; Foxon *et al.*, 2010; Hammond *et al.*, 2013; Hammond and O’Grady, 2014; Chilvers *et al.*, 2017; Hammond *et al.*, 2013; Hammond *et al.*, 2019). An innovative, arguably robust, and ‘whole systems’ evidence base was developed that is distinctive from those devised elsewhere in the UK energy research community in its focus on governance ‘logics’ and structures. The pathways are not predictions or roadmaps; rather they are a way of imaginatively exploring future possibilities, including different approaches to governance, to inform proactive and protective decision-making and enhance the potential for building consensus towards common goals (Chilvers *et al.*, 2017; Hammond and Pearson, 2017).

An initial set of transition pathways for a UK low carbon energy system were developed by applying three main steps (Foxon *et al.*, 2010): (1) characterising the existing energy regime, its internal tensions and *landscape* pressures on it; (2) identifying dynamic processes at the *niche* level [see again Fig. 2 (Foxon *et al.*, 2010)]; and (3) specifying interactions giving rise to, or strongly influencing, the transition pathways and potential branching points on them. They were devised via stakeholder workshops (involving UK energy researchers, industrialists, policy advisers and decision-makers), a narrative descriptive of each pathway, and their subsequent technical elaboration (Barton *et al.*, 2018). The stakeholder workshops were employed by the consortium to distinguish the ‘governance logics’ of three core sets of *actors*: driven by the market, central government intervention, and local community initiatives. Consequently, the three transition pathways were respectively named *Market Rules* (MR), *Central Co-ordination* (CC) and *Thousand Flowers* (TF); each being dominated by a single group’s logic (Foxon *et al.*, 2010; Hammond and Pearson, 2013; Chilvers *et al.*, 2017; Hammond and Pearson, 2017; Barton *et al.*, 2018). Chilvers *et al.* (2017) and Barton *et al.* (2018) summarise the development and high-level analysis of the v2.1 transition pathways set, in order to explain their key features and the distinctiveness and value of the approach, which builds *inter alia* on approaches originally devised by Dutch researchers (e.g., Rip and Kemp, 1998; Geels, 2002; Verbong and Geels; 2007). Thus, the consortium applied the MLP for analysing socio-technical transitions, based on interactions at and between the three levels noted earlier: *niche innovations*, *socio-technical regimes*, and *macro-landscape pressures* (see again Fig. 2).

The development of the UK transition pathways has undergone several iterative loops. Earlier energy analysis and environmental LCA by Hammond *et al.* (2013) related to v1.1 of the pathways. However, a second iteration of these pathways was performed in order to investigate the limitations of that version in terms of technical feasibility, electric grid enhancement needs, social acceptability, energy and environmental performance, and also in the light of the outcomes of the stakeholder workshops (Foxon *et al.*, 2010; Chilvers *et al.*, 2017). Based on the logics of each of the three pathways, using a bottom-up approach, the change of energy use was determined, and the demand by sector was modelled (Barton *et al.*, 2013). The progression of the electricity mix required to meet the demand, while adhering to the logic of each given pathway, was then projected (Barnacle *et al.*, 2013). v2.1 enabled the pathways to be updated in order to incorporate further stakeholder inputs and developments in UK energy policy, as well as inputs from additional modelling. This updating also facilitated a revised life-cycle energy and carbon accounting of the pathways (Hammond and O’Grady, 2014; 2017a; 2017b) with an emphasis on the consequences of upstream emissions from power plants. Subsequently, other environmental and resource burdens of the v2.1 *transition pathways* were evaluated using the environmental or ‘ecological’ footprint technique (Hammond *et al.*, 2019).

4.2 Demand and Supply Portfolios for the UK Transition Pathways

An iterative approach was used to provide quantification of the demand and supply profiles for the UK *transition pathways* to 2050, by iterating between the narrative storylines and exploration of the pathways with a range of modelling and analysis tools (Chilvers *et al.*, 2017; Barton *et al.*, 2018). Key characteristics of the three *transition pathways* are summarised in Table 1 (Foxon, 2013; Chilvers *et al.*, 2017). The starting point for the quantification of *version 2.1* of these pathways was the projection of annual electricity demand by sector from 2010 to 2050 (Barton *et al.*, 2013; Barton *et al.*, 2018). In the MR pathway, annual electricity demand rises from 337 *Tera Watt hours* (TWh) in 2010 to about 512 TWh in 2050 (see again Table 1), due to increasing use of electricity for industry, commercial, transport and domestic space heating and hot water. In contrast, annual electricity demand under the CC pathway rises from 337 TWh in 2010 to some 410 TWh in 2050 (Table 1). This pathway sees electricity demand rising and then levelling off from 2030 onwards, due to increasing use of electricity for transport and domestic space heating and hot water. However, it suggests higher rates of energy efficiency improvements in the domestic sector, and a smaller, highly-efficient industrial sector with lower levels of output (Barton *et al.*, 2013; Chilvers *et al.*, 2017). This would imply that some energy-intensive UK production has moved to other countries, increasing the national consumption of goods produced abroad, implying that UK carbon emissions calculated on a consumption basis would continue to diverge from those on a production basis. Finally, under the TF pathway (Barton *et al.*, 2013; Barton *et al.*, 2018), the annual electricity demand falls from 337 TWh in 2010 to only around 310 TWh in 2050 (Table 1). Despite similar levels of electrification of transport to that in the other pathways, electricity demand falls due to even higher rates of energy efficiency improvements in the domestic and commercial sectors. Again, a small, highly-efficient industrial sector with low levels of output aids the reduction in electricity demand. In all pathways a significant amount of energy is used in industry and commerce for space heating and water heating. The provision of this heat is mostly via the

same technologies as in the domestic sector of each pathway, but often on a larger scale. Thus, in the MR and CC pathways, an increasing amount of electricity is used in heat pumps in the industrial and commercial sectors (Chilvers *et al.*, 2017; Barton *et al.*, 2018). This increase in demand for electricity for heating and hot water is additional to that required for electrification of transport, and it leads to a significant rise in total final electricity demand in these pathways. However, under the TF pathway, the total final electricity demand remains stable up to 2050, as the increase in transport electricity consumption is offset by reductions in demand as a result of energy efficiency improvements. Thus, there is no rise in electricity demand for heating and hot water under the TF pathway, mainly due to the expansion of community-scale renewable *combined heat and power* (CHP).

The energy demand requirements under v2.1 of all the pathways (Barton *et al.*, 2018) are met by rising levels of low-carbon electricity generation, including different generation capacities of renewables, nuclear power and fossil fuels (e.g., coal and, in the future, mainly gas) with CCS, operating at different capacity factors. The detailed generation capacity schedule for each pathway from 2010 to 2050 is reported by Barnacle *et al.* (2013) and Barton *et al.* (2013): see Figures 3-5 (corresponding demand projections were presented graphically by Barton *et al.*, 2018). In 2010, the UK had around 95 *Giga Watts* (GW) of electricity generation capacity, including 29 GW of coal and dual-fuel generation, 33 GW of gas-fired generation, 11 GW of nuclear power, 9 GW of renewable generation and 6 GW of *combined heat and power* (CHP) cogeneration (Barnacle *et al.*, 2013; Barton *et al.*, 2013). Significant amounts of capacity are then required to come on stream under the MR pathway in the 2020s (Chilvers *et al.*, 2017; Barton *et al.*, 2018): see Fig. 3. Subsequently, 21 GW of fossil-fuelled with CCS, 15 GW of nuclear power and 47 GW of renewables (47 GW) by 2030; giving a total capacity of around 130 GW by 2030 (Barnacle *et al.*, 2013; Barton *et al.*, 2013). This deployment leads to further increases in capacity in order to meet rising electricity demand over following decades, particularly from industry and electrification of heating and transport (Chilvers *et al.*, 2017; Barton *et al.*, 2018). Thus, a total of some 168 GW of capacity is installed by 2050, including 44 GW of fossil-fuelled generation with CCS, 26 GW of nuclear power, and 80 GW of renewable capacity, principally from onshore (23 GW) and offshore (30 GW) wind turbines, tidal power (12 GW) and renewable CHP (9 GW).

Similar investments occur in all types of low-carbon generation capacity under the CC pathway during the 2020s (Chilvers *et al.*, 2017; Barton *et al.*, 2018): see Fig. 4; perhaps co-ordinated by a *Strategic Energy Agency*. This could lead to a total of some 122 GW in 2030 (Barnacle *et al.*, 2013; Barton *et al.*, 2013), including high levels of nuclear power (22 GW), slightly lower levels of fossil-fuelled power generation with CCS (18 GW), and less renewables (43 GW). Electricity demand levels off under this pathway, but further power plant deployment would be required in order to increase the capacity to about 151 GW in total by 2050 (Chilvers *et al.*, 2017; Barton *et al.*, 2018). The main contributions are likely to come from nuclear power (30 GW) and fossil-fuelled power generation with CCS (30 GW), although the latter operates at a lower capacity factor (36%), because it again partly provides a back-up for intermittent renewables (65 GW). Finally, action by community groups, as well as local and regional *Energy Service Companies* (ESCOs), under the TF pathway, result in a significant expansion of community-based and micro-scale renewable CHP installed from 2020 onwards (Chilvers *et al.*, 2017; Barton *et al.*, 2018). This reaches a total capacity of 37 GW by 2030 and about

149 GW by 2050 (Barnacle *et al.*, 2013; Barton *et al.*, 2013): see Fig. 5. This is at a similar level to that under the CC pathway, although most plant is made up of renewable generation (112 GW). A significant proportion of demand under the TF pathway is met by local-scale renewables (Chilvers *et al.*, 2017; Barton *et al.*, 2018); from renewable (biogas) communityscale and micro-CHP systems (44 GW), followed by onshore wind turbines (21 GW), solar photovoltaic (PV) arrays (16 GW), and offshore wind farms (8 GW). There are also likely to be some low-carbon investments in earlier periods; possibly leading to 22 GW of fossil-fuelled power plant with CCS and 5 GW of nuclear capacity by 2050.

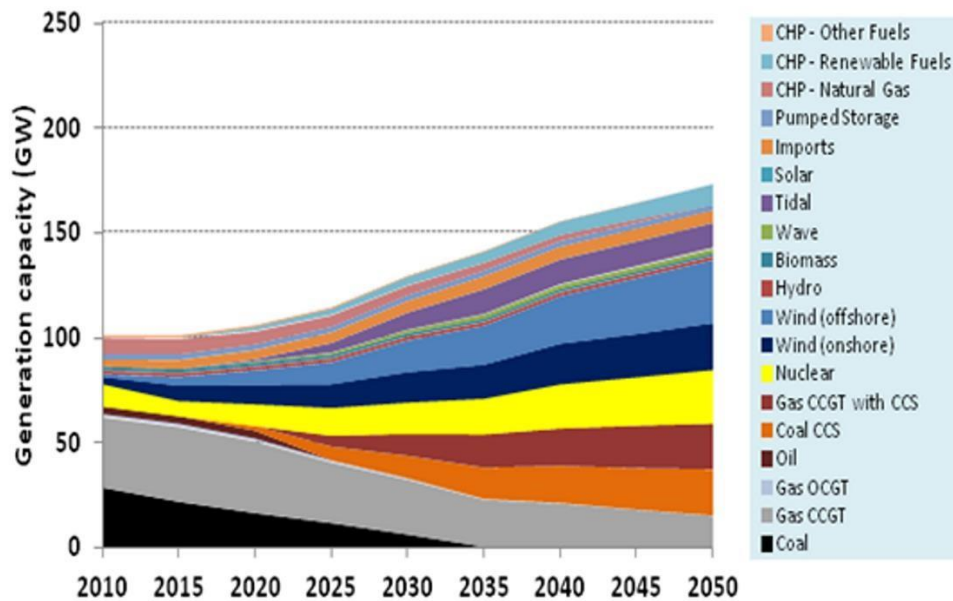


Fig. 3. Generation capacity in the *Market Rules* pathway for the UK.
 [Source: Barton *et al.*, 2018; updated from Barnacle *et al.*, 2013.]

5. Concluding Remarks

A large interdisciplinary consortium of engineers, social scientists and policy analysts have developed three low carbon, more electric transition pathways for the United Kingdom (UK): described as ‘*Market Rules*’ (MR), ‘*Central Co-ordination*’ (CC) and ‘*Thousand Flowers*’ (TF) respectively. The study builds on an approach based on earlier work on understanding transitions, using a multi-level perspective with landscape, regime and niche levels, and its application to the development of ‘socio-technical scenarios’. These pathways to 2050 focus on the power sector, including the potential for increasing use of low-carbon electricity for heating and transport. Here (in Part 1) studies of historical energy and infrastructure transitions have helped understand the dynamics and timing of past transitions, as well as the contexts and conditions that influenced them. Pearson (2018) recently argued that historical analyses offer insights into past energy transitions that are of value to non-historians who study past, current and prospective energy transitions and, where appropriate, to policy-makers who seek to grapple with them.

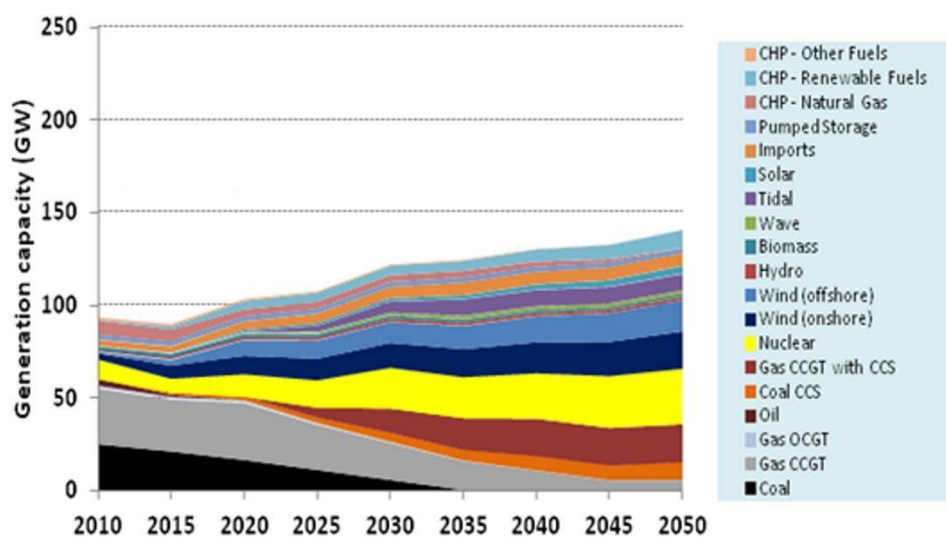


Fig. 4. Generation capacity in the *Central Co-ordination* pathway for the UK. [Source: Barton *et al.*, 2018; updated from Barnacle *et al.*, 2013.]

The extent to which choices need to be made by UK energy policymakers and stakeholders between the large-scale and small-scale *actors*, pathways and associated technologies are discussed (Foxon, 2013; Hammond and Pearson, 2017). Here (again in Part 1 of this contribution) the present UK *transition pathways* are used to highlight the fact that significantly different technological pathways to a low carbon electricity system in the UK by 2050 are possible, although any of these pathways will be challenging to realise. They imply differing levels of efforts and different patterns of risks and uncertainties and approaches to the system's governance. Each exhibits challenges in relation to energy efficiency and behavioural changes, as well as technology choices and their rate of deployment (Barton *et al.*, 2018). The way in which these are addressed and resolved will depend on the governance arrangements of the low carbon transition, including policy measures and regulatory frameworks. So the roles and choices of market, government, and civil society actors are crucial to realising any of these pathways (Chilvers *et al.*, 2017). In a companion paper (Part 2) *horizon scanning* and *energy technology assessments* (ETAs) of the energy technologies that influence the three UK *transition pathways* are employed to provide an understanding the future interplay of the energy policy *trilemma*, i.e., achieving deep GHG emission cuts, whilst maintaining a secure and affordable energy system, and addressing how resulting tensions might be resolved. Indicative ETAs are used to identify the components of a *balance sheet* of technological credits and debits in order to evaluate their societal impacts, and to determine whether they are compatible with Britain's move towards a low carbon future in 2050 and beyond. All three pathways (MR, CC and TF) are evaluated in terms of their environmental performance using complementary *life cycle assessment* (LCA) and footprinting methods. The energy analysis and environmental LCAs reported by Hammond *et al.* (2013) and Hammond and O'Grady (2014; 2017a; 2017b), evaluated v1.1 and v2.1 of the pathways respectively. *Environmental footprint analysis* (EFA) are also employed to estimate the environmental and resource burdens associated with UK power generation based on historic data and the three transition pathways (Hammond *et al.*, 2019). So-called 'disruptive' technological options are examined in order to provide

recommendations on the framing of future energy policy choices that limit the environmental consequences of future electricity systems. It is argued that the value of any new policy direction must be evaluated not only against medium-term climate change (or GHG emission) goals, but against long-term, system-wide goals over a wider spectrum of environmental metrics.

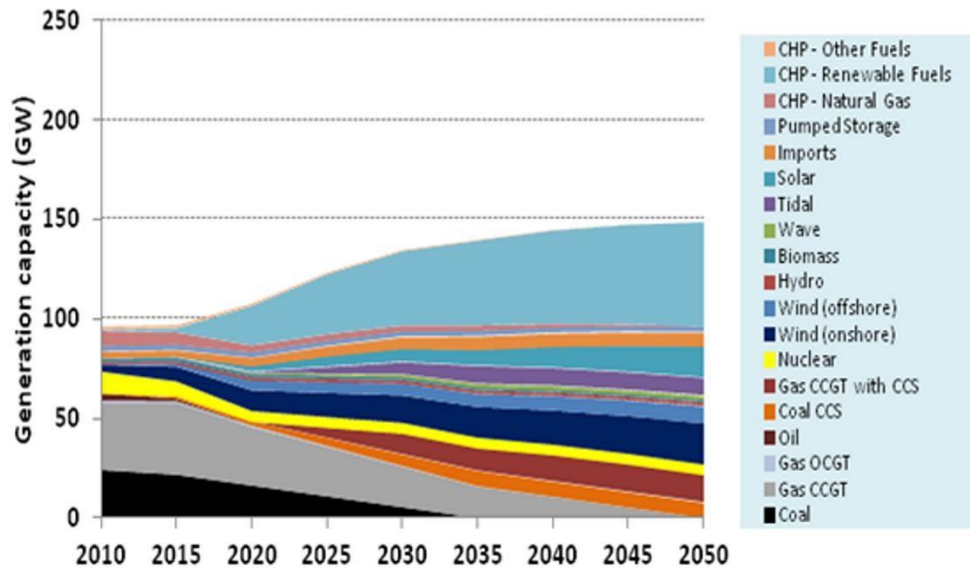


Fig. 5. Generation capacity in the *Thousand Flowers* pathway for the UK.
 [Source: Barton *et al.*, 2018; updated from Barnacle *et al.*, 2013.]

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