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Special Issue -

Realising Transition Pathways to a Low Carbon Future

Guest Edited by

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Background

The evolution of modern industrialised society has been interwoven with discoveries of sources and uses of energy, 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. 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 2008 *Climate Change Act* aimed to establish an economically credible ‘greenhouse gas’ (GHG) emissions reduction pathway towards an 80% emissions reduction by 2050 against a 1990 baseline. It set legally-binding medium and long-term targets, as well as requiring intermediate carbon budgets. These GHG reductions will necessitate a radical transition towards an energy system that delivers high quality energy services through low carbon technologies and processes, whilst ensuring the provision of secure energy supplies at affordable prices: the so-called energy policy ‘*trilemma*’.

There is clearly a need for urgent decisions and substantial investments in supply and demand-side options, against the risks of lock-in to technologies and institutions highlighted in the recent International Energy Agency (IEA) *World Energy Outlook 2016*. In this context the UK *Engineering and Physical Sciences Research Council* (EPSRC) funded the nine-university multi-disciplinary ‘*Realising Transition Pathways*’ (RTP) Consortium, under the auspices of the *RCUK Energy Programme*, over the period 2012-2016. It followed an initial ’*Transition Pathways*’ project (2008-2012), with essentially the same university collaborators, that was funded under a strategic partnership between E.On UK and the EPSRC to undertake a whole systems analysis of the UK electricity sector. Thus, the RTP project built on the first project's three socio-technical *transition pathways*, tools and approaches to analyse the challenges involved in realising a transition to a UK low carbon electricity system in the context of wider European energy developments and policies. In constructing the three pathways, the project focused on aspects of governance. This approach sees a transition pathway arising through the interactions of three broad, highly aggregated types of governance 'logics' (state, market, civil society) and the shifting balances of agency between them and the actors who espouse them. These logics influence the framing of energy challenges and responses, including policy responses. The pathways were named *Market Rules* (MR), *Central Co-ordination* (CC) and *Thousand Flowers* (TF) reflecting three alternative governance 'logics' (*blue*, *red* and *green* pathways respectively). They were developed and analysed via an innovative collaboration between engineers, social scientists and policy analysts. Their research focused on the realisation of technologies, practices and choices that might 'get there from here' on the journey to 2050, and their behavioural, economic and environmental implications. It involved new studies of historical transition experience, strategic issues (including horizon scanning of medium-term technological developments on the supply-side, the network infrastructure, and the demand-side), as well as network, market simulation and behavioural modelling, with 'whole systems appraisal' of key energy technologies and the full pathways, within a 'sustainability framework'. This analysis sought to contribute to an understanding the future interplay of the energy policy '*trilemma*': again, achieving deep GHG emission cuts, whilst maintaining a secure and affordable energy system, and addressing how resulting tensions might be resolved.

The Contributions

The first contribution to the *Special Issue* represents a synthesis by Chilvers *et al.* of the published work of the RTP Consortium that aims to draw out the key 'challenges, insights and opportunities' that have been identified via the research programme. This substantial piece has been co-authored by the 10 Co-Investigators of the EPSRC-funded project. They noted that a low carbon future for the UK would need to see its *Electricity Supply Industry* (ESI) decarbonised by around 2030-2050 in order to give more *head room* for carbon mitigation in other, more challenging sectors (such as industry and transport), including greater use of electricity in providing heat and transport. Such energy transitions are never smooth and always subject to contestation, negotiation and social change. The UK ESI has already undergone quite rapid change over the last few years. Coal power station closures, for example, have amounted to 15 GW between 2010-2015; with the closure of *combined cycle gas turbine* (CCGT) plant and a rapid rise in solar PV systems that now accounts for >1% of UK electricity supply. Moreover, by the third quarter of 2016 low carbon electricity's share of generation accounted for a record high 50.0 %, with increased generation from renewables (wind and solar) and nuclear. The 2016 British Government *energy policy reset* - roughly 30% nuclear, 30% renewables, and 30% gas - could lead to additional changes going forward. But even more dramatic changes will be needed in order to secure a low carbon future for the post-*Brexit* UK by 2050. In order to analyse such challenges he RTP Consortium adopted the practice of joint working: we explored and integrated different kinds of expertise and provided opportunities for reflection and evaluation, leading to the co-production of knowledge designed to address the multi-faceted challenges of climate change and the energy *trilemma*. Analytical tools were developed and applied to assess the technical feasibility, social acceptability, and environmental and economic impacts of the pathways. It became evident that socio-technical solutions are required on both the demand and supply-side of any future UK energy system. The insights gained from this exercise provide a valuable evidence base for developers, policy makers, and other stakeholders. They are laid out via *bullet point* summaries at the end of each principal section of the Chilvers *et al.* paper.

The remaining papers in this *Special Issue* are all new contributions by the various RTP Co-Investigators and their researchers that have not been previously published. Pearson & Arapostathis examined two centuries of historic change in the UK gas industry in order to identify the socio-technical innovation, governance changes involved in six key transitions and to considering what insights from these past experiences might imply for the future of the UK gas system and its networks, especially for natural gas. The paper examines: the origins of the system by Murdoch, Boulton and Watt; the early 19th century development of local gas networks; innovative responses to, inter alia, the challenge of incandescent electric light from the 1880s; and three later transitions. The analysis by Pearson & Arapostathis has shown that from its origins the gas industry has proved remarkably resilient to external and internal uncertainties, to new competition, technologies and resources, and has shown the ability to experiment and eventually to adapt. Over this period the transitions were dominated by varieties of the market logic in situations where the UK Government mainly exercised a regulatory role. The exception was the post-WWII period (the '*fifth transition*'), where endemic economic and organisational problems and the new Labour Government drove the State towards socio-technical amalgamation and centralisation. This saw the industry nationalised in 1948, as the multi-fuel economy developed, and then the bold conversion to North Sea natural gas in the 1960s, followed by the privatisation of *British Gas* in 1987. Pearson & Arapostathis argue that the current global, national and regional challenges have resulted in hybrid governance patterns that enhance the roles of national and regional governments in the guidance of energy transitions. Thus, they believe that the State is at a stage of reorientation, reconfiguration and renegotiation in an ongoing *seventh, low carbon transition* with significant implications for the future of the UK gas system, its networks and feedstocks. New challenges faced by the sector include techno-scientific uncertainties, global negotiations and agreements about climate change and trade, changing national priorities, post-2008 fiscal and economic challenges and, most recently, the fallout from public deliberation and democratic decisions, especially Brexit.

Pudjianto & Strbac examine the benefits of *Demand Side Response* (DSR) in reducing the capacity of power system infrastructure and stabilising the electricity prices in different future system backgrounds. The impact of DSR has been investigated using a *Whole-electricity System Investment Model* (WeSIM) [see also Chilvers *et al.*]. It is a holistic and comprehensive electricity system analysis model simultaneously balancing long-term investment-related decisions against short-term operation-related decisions in light of the flexibility provided by DSR, across generation, transmission and distribution systems, in an integrated fashion. In this context, WeSIM is used to determine the peaking generation, transmission and distribution capacity required for three different UK transition pathways to ensure efficient and secure operation of the system. A key feature of WeSIM lies in its capability to simultaneously consider system operational decisions and infrastructure additions, with the ability to quantify trade-offs between alternative smart mitigation measures, such as DSR for real-time balancing and transmission and distribution network and/or for generation reinforcement management. The model also captures potential conflicts and synergies between different applications of distributed resources in supporting intermittency management at the national level and reducing necessary reinforcements in the local distribution network. The impact and value of DSR driven by a whole-system approach is compared to those that Pudjianto & Strbac regard as *silo* approaches, including *Transmission System Operator* (TSO) or *Distribution System Operator* (DSO)-centric DSR applications. The importance of control co-ordination between TSO and DSO for optimal DSR is therefore discussed and highlighted. Model results indicate that DSR can provide significant savings across all the *transition pathways*. By 2020, the gross benefits are in the range of £1.2 – 2.9 billion (bn) per year while the value increases up to £5.6 bn per year by 2050; albeit with significant uncertainties caused by those in the input data.

The end-use of electricity has become an ever more important component of the UK energy system. Electricity is increasingly used in the home, in the service sector, in industry, and in the wider *United Kingdom* (UK) economy. Allen *et al.* examined electricity end-use in these sub-sectors in order to estimate how much is employed for heat and power applications respectively. The share of electricity used for heat and power purposes was therefore determined from a baseline of 1970 (when the share of electricity used to meet these end-use heat demands was ~45%). Alternative scenarios for the future development of the UK energy system were then used to estimate the variation in *heat/power* share out to 2050. It was found that the proportion of electricity used to meet these end-use heat demands in the three sectors examined were likely to be quite high (~50-60%), and that these shares appear insensitive to the precise nature of the forward projections (forecasts, transition pathways or scenarios). These findings show a significant amount of end-use power consumption in the three UK demand sectors considered by Allen *et al.*: in households, services, and industry. The results represent a first indicative analysis of possible long-term trends in this heat/power share across the UK economy. Thermodynamic (*energy* and *exergy*) analysis can give rise to differing insights into the relative merits of the various end-uses of electricity for heat and power. The thermodynamic property known as ‘exergy’ reflects the ability to undertake ‘useful work’, but does not represent well *heating processes* within an energy sector. *Heat* has a variable thermodynamic quality depending on the ratio of the process temperature to the environmental temperature or datum. Where end-use *heat* demands are met by electricity, Allen *et al.* argued that energy and exergy analysis should be performed in parallel in order to reflect the interrelated constraints imposed by the *First* and *Second Laws of Thermodynamics*. An understanding of the end-uses for electricity provided by this study will enable policy makers to take account of the implications of a greater end-use of electricity in the future.

The global target to achieve decarbonisation suggests an increasing penetration of electric vehicles (EV). Wang *et al.* assumed a smart grid framework whereby the driving patterns for

EVs are known, time variations in electricity prices are communicated to householders, and data on voltage variation throughout the distribution system are available. The power demand due to uncontrolled EV charging coincides with the daily UK electricity load peak in the early evening, which would clearly be a threat to the power system as the number of EVs increase. On the other hand, the current and future power network could benefit if the EV owners actively participate in *Demand Side Management* (DSM) of both EV charging and discharging actions. The smart grid framework employed an aggregator to gather information from individual EV owners. It accessed the schedule of EV charging and discharging actions throughout the day in response to a *real-time price* (RTP) signal. Participation by private EV owners in DSM was assumed to be motivated by energy cost minimization associated with EV use. A domestic network was investigated whereby the local EV penetration level was assumed to be 100%. EV use patterns were extracted from the UK *Time of Use* (TUS) survey data in 10-minute resolution and the domestic base load was generated from an existing model [developed at Loughborough University]. A dynamic optimal power flow simulation for a period of 24 hours was implemented in *OpenDSS* so as to solve the optimization problem. The best results gave an EV charging cost of £10.86 for the investigated distribution network, which was very close to the proposed heuristic solution to the smart charging case (£10.92), therefore demonstrating the potential effectiveness of the proposed method of EV charging cost minimisation.

Hammond & O'Grady evaluated the three UK *transition pathways* to a more electric low carbon future out to 2050 in terms of their life-cycle energy and environmental performance within a wider sustainability framework. Electricity decarbonisation, while providing a secure and affordable supply, can lead to varying life-cycle environmental consequences. The 2016 British Government *energy policy reset* (referred to above) recognised, for example, that one of the most cost-effective contributions towards GHG emission reductions from electricity generation may be achieved by replacing coal-fired power stations with gas-fired plant. Consequently, the Government has proposed to close coal stations by 2025. But such steps towards electricity decarbonisation can lead to varying 'whole systems' environmental consequences. The resulting environmental impacts have therefore been appraised using the most recent version of the *transition pathways* by Hammond & O'Grady on a life-cycle basis from 'cradle-to-gate'. They were coupled with three different UK energy futures specifically based on (i) the phase-out of coal use in favour of gas-fired power and nuclear generation, (ii) ranging penetration levels of *carbon capture and storage* (CCS), and (iii) the allocation of different fuel type in the context of *combined heat and power* (CHP). The roles of energy efficiency and fluctuations in electricity demand across all pathways were also investigated. Thus, the impacts of recent technological trends in UK energy policy, and their effect on the pathways were explored through a series of sensitivity analyses. So-called 'disruptive' technological options were examined in order to provide recommendations on the framing of future energy policy choices that limit the environmental consequences of future electricity systems. This study shows that the guiding principles of environmental *life-cycle assessment* (LCA) provide a valuable tool to measure the effects of proposed policy decisions and, in the case of bioenergy options, help shape new policy choices ahead. Hammond & O'Grady noted that shifting energy policies had different impacts depending on the future pathway and disruptive technologies examined, but they indicate that environmental trade-offs were unavoidable. They argue 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.

Barton *et al.* utilised an hour-by-hour time-step analysis of Great Britain (GB) grid balancing in low-carbon energy futures via the UK Government's *DECC 2050 Calculator*. Parallel detailed modelling employed the *Future Energy Scenario Assessment* (FESA) tool, together with real weather data and real electricity demand data from year 2001. It was used to model future supply and demand profiles suitably adjusted to reflect technology uptakes. Calculation of net demand (total demand, less intermittent renewables and inflexible portions of other electricity generation) revealed the magnitude and duration of peaks and troughs throughout the year. This permits quantification of required peaking plant, energy storage, demand response, or combinations of these technological options. The results indicated that the grid balancing challenge is generally much greater than is apparent from the *DECC Calculator*, with significant excess power from renewables and less flexible generators needing to be exported or curtailed. However, the *Calculator* fails to calculate how much electricity is actually in excess of what can be exported. FESA suggests that power surpluses can persist for many days, and indicates the importance of developing long-term energy storage technologies (days and weeks, not just hours), including power-to-gas technologies. The results of Barton *et al.* therefore underline the value of energy storage, particularly in a high-renewables future. In contrast, demand shifting appears to give rise to only a slight improvement in grid balancing. When analysed using FESA, all the example DECC 'pathways' result in a lower capacity factor for CCS and biomass generators than indicated in the *DECC 2050 Calculator* itself. It is therefore doubtful that these generators, especially some of those with CCS, can be financially viable under the DECC 'pathways'. Thus, short-term time-shifting as a means of *demand response* appears to have very limited benefit to grid balancing, but fuel-switching technologies show some promise, particularly in terms of flexibly using electricity instead of a fuel.

The Scottish Government aims that 100% of electricity consumed in Scotland should be supplied by renewable, zero carbon sources by 2020. This continues to drive change in the energy system, alongside associated European and UK targets. The growth of renewables in Scotland is being seen at many scales, including industrial, domestic and community generation. In the latter two cases, a transition from the current 'top down' energy distribution system to a newer approach is emerging. Consequently, Robertson & Galloway take a 'bottom up' view that sees community-led distributed energy at its centre. Their contribution employed the *Hybrid Energy System Analysis* (HESA+) modelling tool to investigate high penetrations of distributed generation (DG) in Angus on the East Coast of Scotland. Installations of the DG followed the TF *transition pathway*, which sees more than 50% of electricity demand being supplied by DG by 2050. Insights were gained into the technological and socio-political feasibility and implications of high penetrations of DG in the Scottish energy system. Simulation results showed that with a constrained network system, exports were only 17.5% of those of a non-constrained network with sufficient network capacity; moreover, household revenue was curtailed to only 5% of the maximum capability. The results also indicate the influence that system change will have on regional and local emission levels under four separate scenarios Robertson & Galloway considered in their study. It is shown that the penetration of DG requires supplementary installations of reliable and long-term storage, alongside utilisation of transmission and transportation infrastructures to maximise DG potential (and ‘whole system’ benefits). Alongside storage, installation of new heating technologies is essential (along with DG) as Scotland’s energy sector transitions towards 2050. GHG emissions from natural gas-fired heating systems were the main contributor to domestic emissions in the Angus region simulations. It is therefore important that technologies such as biomass-fired heating units and/or heat pumps are considered as part of the strategy to increase renewable heat in Scotland. Importantly, Robertson & Galloway argue that there must be a level of co-ordination and support to realise a shift to a *highly distributed energy future* in order to ensure there is a strong economic case with a reliable policy backing.

McKenna *et al.* studied the impact on carbon dioxide (CO_2) emissions from electrical storage systems added to Irish power systems with high penetrations of wind power. [CO_2 is the main GHG with a residence time in the atmosphere of around 100 years.] Storage systems incur energy losses due to their inefficiency, thereby increasing total system demand. The in-use impact of storage is linked to this overall increase in demand, and the carbon intensity of the resulting supply-mix will impact on their associated GHG emissions. If this increase is met entirely by increases in generation from renewables (for example, by reduction in wind curtailment), then this would result in a positive impact. The actual impact, however, will depend on factors such as the storage technology, its operation and efficiency, the marginal CO_2 emissions rate of the national electricity system, and operational constraints linked to system non-synchronous generation limits. McKenna *et al.* have systematically considered these factors, taking the Irish All-island power system as a real-world case-study study. Data on the observed dispatch of each large generator for the years 2008 to 2012 was used to estimate a marginal emissions factor of about 0.55 $kgCO_2/kWh$. The findings clarify the non-trivial nature of assessing the carbon impact of storage in power systems with high penetrations of wind power. They also quantify the factors that will influence whether electricity storage will have a positive or negative impact on the Irish power system. These results suggest that CO_2 emissions increase in the short-run for all storage technologies when consistently operated in ‘peak shaving and trough filling’ modes. McKenna *et al.* believe that such findings should also be true for the GB and US power systems.

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