



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Beyond the disruption narrative

Citation for published version:

Winskel, M 2018, 'Beyond the disruption narrative: Varieties and ambiguities of energy system change' Energy Research & Social Science, vol. 37, pp. 232-237. DOI: 10.1016/j.erss.2017.10.046

Digital Object Identifier (DOI):

[10.1016/j.erss.2017.10.046](https://doi.org/10.1016/j.erss.2017.10.046)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Energy Research & Social Science

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.



Beyond the Disruption Narrative: Varieties and Ambiguities of Energy System Change

by Dr Mark Winskel

Chancellor's Fellow and Senior Lecturer
Science, Technology and Innovation Studies Group
School of Social and Political Science
Chisholm House, High School Yards
University of Edinburgh, Edinburgh EH1 1LZ
Email: mark.winskel@ed.ac.uk

Abstract

For many observers we are entering an age of heightened disruption in energy systems - a 'disruption narrative' is now prominent and seemingly widely-shared. The energy disruption narrative often goes beyond the merely descriptive: it is also often used in a normative way, in that system disruption is seen as a necessary and welcome enabler of the shift to more sustainable and more rapidly decarbonised energy systems. While not denying that there are significant changes underway in the operation and governance of energy systems, I reflect here on the assumptions associated with the disruption narrative and its value as a guide to policy and research. I firstly review some theoretical and empirical research on disruptive innovation, consider some empirical evidence on historic energy system change, and then reflect on the value of a disruptive narrative in 'energy futures' research and policy. The disruption narrative is a contestable framing for researchers, across both 'whole systems' analysis and more specific technological and organisational level study, and is a problematic guide for policy. Researchers and policymakers should be sceptical of uniform narratives about change, and seek more balanced attention to both disruptive and continuity-based dynamics of energy system change and sustainable transitions.

Keywords

Energy; innovation; continuity; disruption

Introduction

For many observers we are entering an age of heightened disruption in energy systems – among energy professionals and analysts a 'disruption narrative' is now prominent and seemingly widely-shared. The President of the UK Energy Institute recently suggested that 'today's energy system is undergoing a quiet revolution, driven by an everchanging global political landscape, climate change challenges and a range of innovations influencing energy consumption' (Energy Institute, 2017, p4). The International Energy Agency, in its most recent analyses of global energy system change, has concluded that this is 'a momentous period for global energy' (IEA, 2016) and 'the energy mix is being redefined' (IEA, 2017). The consultancy firm PricewaterhouseCoopers has articulated a vision of rapid and dramatic change: 'the pace of technology-driven change is accelerating well beyond the speed the power sector believed possible. From a scale-driven, centralised and standardised model, the sector is set to evolve to one that is digital, distributed and personalised' (PwC, 2016).

The energy disruption narrative often goes beyond the merely descriptive: it is also often used in a normative way, in that system disruption is seen as a necessary and welcome enabler of the shift to more sustainable and more rapidly decarbonised energy systems, and an essential means of escaping the locked-in unsustainabilities of incumbent systems. This carries significant policy and regulatory implications: it implies that policymakers and regulators should seek to actively unleash

disruptive forces (perhaps by destabilising and dismantling incumbent interests) so as to clear the path for the sustainability transition.

While not denying the significant changes underway in the operation and governance of energy systems, I want to reflect here on the assumptions associated with the disruption narrative and its value as a guide to policy and research. I firstly consider the theoretical and empirical background to disruptive innovation, consider some historic empirical evidence on energy system change and then the value of a disruptive narrative in 'energy futures' research and policy. I will argue that the disruptive innovation is a disputable framing for researchers, across both 'whole systems' analysis and more specific technology- and organisational-level study, and is a problematic guide for policy. I conclude that energy systems researchers and policymakers should be sceptical of uniform narratives about change, and should offer more balanced attention to both disruptive and continuity-based dynamics of energy system change and sustainable transitions.

In their benchmark collection of research on energy technology innovation, Charlie Wilson and Arnulf Grubler (Wilson and Grubler, 2014, p.7) define 'radical', 'breakthrough' and 'disruptive' innovations as those novelties that strongly deviate from prevailing technological and institutional norms, while 'incremental' or 'continuous' innovations are defined as improvements without any fundamental novelty in end-use service provision. Although these definitions capture the essence of research and policy debates on disruptiveness, they also reflect the compound and ambiguous character of the objects of analysis here, spanning a mix of social & technical, and upstream & downstream concerns. Rather than aiming explicitly at any more precise definition of disruptive and continuous innovation (an ultimately futile pursuit given the multiplicities of voices and framings involved), my aim here is to explore the tensions and problems involved in their application – ambiguities which were evident in the workshops which were the genesis for this series of articles (Wilson, 2017).

Theoretical and Empirical Backgrounds

Disruptive and radical innovation are longstanding preoccupations in applied social sciences such as innovation studies, technology studies, organisation studies and business studies. Much of this research is focused on firms and organisations rather than larger systems, and much of it takes its inspiration (knowingly or implicitly) from Joseph Schumpeter's work in the early and mid-twentieth century. Schumpeter understood broad patterns of industrial and economic change as reflecting a 'perennial gale of creative destruction' (Schumpeter, 1994 [1942]).

The most prominent recent contributor to disruptive innovation research has been Clayton Christensen. In his 'Innovator's Dilemma' (Christensen 1997), Christensen argued that it was profoundly difficult for incumbent firms to direct sustained effort and resource on disruptive innovation. Firm capabilities, forged within 'value networks', are deeply oriented to 'sustaining innovation', and are more specialised and path dependent than is commonly assumed. Disruptive technologies present intrinsic conflicts – they rarely 'make sense' to large established companies – and so tend to be left to small outsider firms to develop.

Christensen's thesis has been repeatedly challenged; Daneels (2004), for example, criticised it for a selective reading of empirical evidence, for only picking 'winning' disruptive technologies and for overstating the innovative inertia of incumbent firms. It has also been widely misapplied – Christensen et al. (2015) recently stated that 'disruption theory is in danger of becoming a victim of its own success ... the theory's core concepts have been widely misunderstood and its basic tenets frequently misapplied'.

Nevertheless, the thesis still often sets the terms for contemporary debate on disruptive innovation, with many other relevant studies over the past 30 years often left unreferenced. Rather like Christensen et al.'s recent contribution, much of this under-examined work seeks a more nuanced and heterogeneous account of innovation, spanning both disruptive and continuity-based dynamics. Contributors here can be traced back to well before Christensen's debate-defining account. Many of the theoretical claims involved are based on detailed longitudinal studies of multiple firms and industry sectors; a few such studies are now briefly reviewed.

Abernathy and Clark (1985) suggested that disruptive innovation was a problematic and ambiguous term. Rather than any universal or essentialist properties, disruptive innovation forces were highly relative and situated, and analysis needed to consider their varied influence on producers, users and markets. Drawing on innovation patterns in the US auto industry, Abernathy and Clark distinguished between 'architectural innovations' (which are both technologically and socially disruptive), and 'regular innovation' (which builds on established competences). The latter, they concluded, although 'almost invisible', can have a dramatic cumulative effect. Although the analytical gaze tended to be drawn to novel innovations, novelty (and scientific advance more generally) may carry less significance, over time, than relatively mundane changes.

Tushman and Anderson (1986) noted that technological discontinuities were not necessarily organisationally disruptive – indeed some could be 'competence enhancing'. Based on detailed longitudinal studies of computing, cement and airline industries, they concluded that such were the varieties and complexities of innovation dynamics at firm and sector level, disruptive innovations (and dominant designs) could only be identified in retrospect. Anderson and Tushman (1990) distinguished between eras of ferment and incrementalism, and considered how some organisations were able to develop 'ambidextrous' competences to prosper in both. Tushman and Rosenkopf (1992) saw discontinuities as 'rare and unpredictable', and again, not knowable in advance.

Some analysts offer more explicit criticism of Schumpeterian-based accounts of economic and technological change. For the technology historian David Edgerton much scholarship is uncritically focussed on novelties, with an 'enormous rhetorical emphasis' on innovation in studies of public technology policy (Edgerton, 2010). (For a 'long history' of the emergence and deployment of the term 'innovation', see Godin, 2010). For Edgerton (2010) such accounts offered a 'narrow progressivism', with innovation-deterministic theory often standing in for detailed empirical study. Schumpeterian-based economic and technology histories, he concluded, were often 'absurdly' innovation-centric. Paul Edwards (2003) has also been critical of the preoccupation with novelty and emergence in much technology studies.

As readers of this journal are likely to be aware, these debates are also played out in more contemporary (and futures oriented) innovation studies debates, especially sustainable transition studies. Disruptive innovation plays an important role in transitions theory, reflecting its origins in constructivist sociology and evolutionary economics (Schot and Geels, 2008; Paredis, 2011; Winkler and Radcliffe, 2014). For example, Andrew Van de Ven et al.'s 'Innovation Journey' (Van de Ven et al., 1999), an important influence on transitions theory, explicitly invoked Schumpeterian 'creative destruction' in developing their emergent model of innovation. For Van der Ven and many other innovation studies theorists, the key actor perspective is that of the disruptive entrepreneur or niche firm, rather than any wider institutionalist or structuralist perspective.

Although later versions of transitions theory have been more attendant to wider societal structures and institutions, many transitions theorists still often presuppose that disruptiveness is a necessary requirement for system innovation (e.g. Voß et al., 2009), with incumbents typically defined by their commitment to inherently limited incrementalism (e.g. Markard et al, 2012). It should also be noted

that some transitions scholarship *has* recognised that the technological and organisational constitution of disruptiveness (and the role of incumbents in transitions) varies greatly according to context (e.g. Raven, 2007; Geels et al., 2016).

Another prominent strand of sustainable innovation studies, Technological Innovation Systems (TIS) theory, also has its origins in evolutionary understandings of innovation which emphasise firm-level variation and selection (Nill and Kemp, 2009). According to Suurs and Hekkert (2012: 154) for all 'quasi-evolutionary theories' (listed as strategic niche management, the multi-level perspective, technology innovation systems and transition management), 'a transition is *regarded* as a regime shift ... through an accumulation of niches that interact with a destabilizing regime' (emphasis added).

From an energy systems perspective, the suitability of Schumpeterian based accounts for closely coupled and network-based systems needs to be questioned. In Van de Ven's terms (Van de Ven et al., 1999), such systems may be thought of as being heavily conditioned to *convergent* rather than divergent innovation (i.e. based around standards and inter-operability). Tushman and Rosenkopf (1992) noted that innovation in systems-based technologies had a distinctive emphasis on hierarchy. Raven (2007) suggested that given their tight coupling and high entry barriers, regime hybridisation (rather than niche accumulation) may be the route for system change in infrastructure-based technologies; as Robert Fri noted, innovation in such sectors is typically 'incremental, cumulative and assimilative' (Fri, 2003).

This is not to deny that energy system lock-in and path dependency can present barriers for sustainable innovations and transitions. System lock-in is a well-recognised concern among some technology systems historians and theorists. Thomas Hughes (1983) noted that as socio-technical systems became surrounded by supportive institutional, legislative and financial arrangements they developed an in-built conservativeness, and an orientation to incrementalism. Arnold Pacey (1983) recognised that bureaucracies tended to develop a characteristically incremental pattern of technological change, but noted also that there were 'crucial moments of recognition' when a varied collection of different factors fit together and a new form of practice takes off.

Rather than taking sides in a polarised debate based on disruption and continuity, the broad insights offered by scholars such as Hughes and Pacey relate to theoretical caution and analytical scepticism, based on a deep commitment to empirical inquiry. Pacey (1983) warned against the use of any essentialist or determinist notions such as 'technological imperatives' enrolled to support or oppose particular developments; such claims, he suggested, often served political purposes and were in-part an expression of values and interests – including the interests of some innovators to promote their work.

Paul Nightingale has argued that 'Chandlerian accumulation' rather than 'Schumpeterian destruction' is a more accurate characterisation of change in industries characterised by scale, inertia and regulation (see, for example, Nightingale and Martin, 2004; Nightingale and Mahdi, 2005). Like Pacey, Nightingale has invited analysts to consider what may lie behind claims for disruptiveness, and how disruptive narratives could serve particular interests. For example, for national governments, a focus on small firm entrepreneurship and radical innovation may divert attention from inadequate support for more mundane, incremental (but potentially more impactful) support programmes. While inflated expectations, optimism biases and hype are *required techniques* for entrepreneurs and small firms, as they strive to command attention and resources, they should be treated with scepticism by more independent analysts, regulators and policymakers.

A body of more recent infrastructure transitions scholarship has sought to align the Hughesian tradition of deep histories of socio-technical systems with contemporary concerns for sustainability and energy innovation (e.g. Högselius et al., 2013). Based on a historical analysis of European electricity and gas infrastructure development, Van der Vleuten and Högselius (2012) called for a 'symmetrical analysis' of regime stability and change in transitions studies, rather than any ex-ante commitment to disruptiveness and regime overthrow, with futures oriented analysis attending to how scenarios of change placed greater or lesser emphasis on disruption and continuity (or incumbency and new entrants).

Energy innovation dynamics

Studies of both historical trends and more recent changes (including low carbon innovations) suggest that continuity-based dynamics often play an important role in energy innovation, at both organisation and systems levels. At an organisational level, for example, Stenzel and Frenzel (2008) reported a spectrum of proactive, reactive and resistive responses to new technologies among European utilities. Combining transitions and technology strategy literatures in a study of the heavy vehicle industry, Berggren et al. (2015) found a diversity of strategies among incumbents, with some able to take positions in niches while simultaneously retaining their established activities.

Bergek et al. (2013) also found a diversity of incumbent responses in transport and energy sectors, noting that this confounded assumptions of incumbent inertia and resistance based on Schumpeterian theory. Discontinuities seldom led to creative destruction, they concluded; instead, Keith Pavitt's concept of 'creative accumulation' offered a more accurate account of change in some sectors. Bergek et al (2013) called for more research on creative accumulation, in terms of the dynamic integration of old and new competences.

Drawing on the corporate strategy literature, Bowen (2011) identified a mix of 'sustaining' and 'disruptive' technology propositions within a single energy technology field such as carbon capture and storage (CCS), according to the particularities of technology design and an organisation's position on the supply chain. Although CCS is usually considered a 'sustaining innovation' in Christensen's terms (and has therefore received very little attention within transitions research, other than as a reactive response by incumbents to regime destabilisation pressures), Bowen argued that one form of CCS – pre-combustion capture technology – has disruptive potential, in terms of its links to the hydrogen economy, thereby redefining the trajectory of the energy sector.

In their longitudinal study of lighting, Franceschini and Alkemada (2016) highlighted the different dynamics of innovation associated with different technologies (fluorescent, compact fluorescent, and LED). LED technology, though it has changed the technological regime in the lighting industry – as well as having a step-change impact on energy demand and GHG emissions from lighting services – was described as an example of a relatively non-disruptive innovation, in terms of its effects on markets and firm strategies, and its strong links to related industries.

There is also some quantitative evidence that continuity-based innovations such as process efficiencies, fuel switching, technology substitution and end use efficiency can have dramatic cumulative impact on energy systems over time. For example, such changes have been important factors behind the very substantial reductions in UK carbon emissions over the past 30 years. Overall, UK GHG emissions are now 42% below 1990 levels, while over the same period the economy has grown by over 60% (CCC, 2015). Between 1990 and 2009, improved conversion efficiencies and fuel switching led to a reduction in effective UK electricity sector CO₂ emissions of 36.5% (DECC 2010). Average household energy use in the UK (mainly associated with buildings' heating) has fallen by almost 30% between 2004 and 2015, largely as a result of improved buildings insulation and the

roll-out of more efficient gas boilers (UKERC / CIED, 2017). Public policy support for rather mundane innovations has been central.

Finally, there is also some evidence supporting continuity-based public innovation programmes. For example, Richard Newell's review of decades of US federal RD&D energy investments highlighted the powerful impact of continuity-based innovation programmes over time (Newell, 2011). In areas such as resource extraction and processing, engine efficiencies and industrial process efficiencies, decades of incremental change had led to major productivity gains and significantly reduced the costs of pollution abatement. Newell attributed this to the successful leveraging of incumbent interests and resources. By comparison, more radically oriented programmes, such as on synthetic fuels, had produced much less impact.

Prospective studies

Going beyond any single dominant narrative about energy system futures reveals a wide-ranging contemporary debate among innovation theorists on the merits of different styles of energy innovation governance – including greater or lesser emphasis placed on disruption and continuity. In their survey of research policy since the early 2000s, Winskel and Radcliffe (2014) distinguished between niche-based, continuity-based and breakthrough governance prescriptions. For example, Perrow (2010) argued that while decentralised approaches were appropriate for some parts of the energy system (such as energy efficiency) a centralised top-down approach *was* appropriate for large-scale technologies such as carbon capture and storage.

Konrad et al. (2007) considered prospective regime dynamics for utility industries. In doing so, they explicitly questioned the regime-overthrow account of transitions, suggesting that this was likely to be especially restricting for future-oriented research: 'we should not presuppose that a regime shift is necessarily the one best way' (Konrad et al., 2007, p. 1192). Gregory Unruh (2002) concluded that under high carbon lock-in, disruption-based strategies were less likely to bring about rapid change than more continuity-based approaches (see also Hargadon, 2010).

A number of analysts suggest a portfolio of measures combining continuity and disruption, evolving over time (e.g. Unruh and Carmillo Hermosilla, 2006; Weiss and Bonvillian, 2009; Lester and Hart, 2012). The complex interdependencies of systems are likely to present difficulties here, in terms of allowing for both regime stabilisation and destabilisation, and progressing both established and radical innovations. Walker (2002, 9834) noted the ambiguous nature of system lock-in, in that it is both a 'dangerous' but 'essential' facet of complex infrastructure innovation.

There is also an emerging emphasis on hybrid combinations of the old and new in transitions scholarship. Markard and Hoffmann (2015) developed a typology of complementarities between established and emerging industries, to systematise understanding of how new industries may emerge from the old, in terms of changed selection environments, links between industries and knowledge bases, and complementarities (financial, knowledge and human). Makitie et al. (2016) analysed the complementarities between established and emergent energy industries such as between oil and gas and offshore windpower.

A number of scenario studies have explicitly addressed the issue of incumbency and disruption. For example, Kemp (2011) distinguished between disruptive and sustaining innovations, with some technology fields pre-assigned (e.g. CCS as a sustaining innovation and smart grids as disruptive). These ex-ante typologies may be questioned in light of the discussion above, in that they risk essentialist and determinist outcomes, with incumbency hardwired to limited incrementalism, and with analysis rendered insensitive to more heterogeneous roles. Scenario designs which allow for

more permeable relationships are needed here, better reflecting the ambiguities and unpredictabilities of innovation.

In this context it is useful to study energy scenario practice, both historically and as pursued more recently since the rise of climate change concerns. One of the striking findings from McDowall et al.'s (2014) post-hoc review of UK energy scenarios was the unexpectedness of change, in that actual developments often lay outside the ranges of imagined futures: developments considered highly unlikely can and do materialise. Because scenario exercises tend to reflect the prevailing forces and interests at the time of their development, important drivers were often downplayed or overlooked, especially 'softer' aspects such as institutional or governance changes.

For McDowall et al. (2014) this implied more attention to the range and character of uncertainties referenced in scenario exercises, and the tools and techniques involved. Historical 'successes' in the use of scenarios had tended to be achieved through opening up dialogue on energy priorities, by challenging established thinking and creating plausible alternative narratives. Methodologically, this required processes to incorporate a diverse range of stakeholders and experts to articulate and contest energy system goals and choices. McDowall et al. (2014) also noted the substantial accumulated evidence on cognitive biases and limits (such as availability heuristics, conjunction fallacies and framing, elaboration and confirmation biases) which shape any individual or collective view of the future.

The UK Climate Change Act of 2008 – with its statutory combination of long term decarbonisation and step-wise carbon budget limits – presents a forceful institutional setting for energy scenario development in the UK. Within this, much recent analysis has turned to the future of buildings heating. The CC Act implies a near-wholesale shift away from the dominant form of heating buildings – unabated natural gas – by 2050 (Eyre and Baruah, 2014). However, there is no consensus about the UK's low carbon heating transition pathway; rather, there is a range of possible pathways, with very varied combinations of disruption and continuity (Carbon Connect, 2014).

For example, the future of the UK's natural gas national pipeline infrastructure – the incumbent system by which heating is currently provided to around 4/5ths of UK homes – is now contested between advocates of repurposing and renewal (for example, to allow for a transition to hydrogen-based heating), and run-down and decommissioning (for example, to allow for a transition to local heat networks). There are also significant differences in the envisaged pace and extent of the UK heat sector transition, across more gradualist and more transformational visions (CCC, 2016; Lowes et al., 2016; Policy Exchange, 2016).

Winkel (2014) reviewed a number of recent UK energy system and buildings heating scenarios. In the early period after the CC Act, a radical vision for the future of heating was established among mainstream, 'official' analysts in the UK Government and the Committee on Climate Change (CCC), involving the near wholesale electrification of heating by 2050, using analysis based largely on whole systems modelling studies. Under a combination of more detailed modelling and emerging evidence from field trials and early deployment, this radical blueprint was soon challenged, and more recent scenarios have tended to greater technological diversity, including mature technologies or hybrid combinations of the old and new (see also Eyre and Baruah, 2014). Winkel (2014) concluded that the case showed the constructive role, in scenario development, of dissident visions which challenged mainstream consensus views.

In their analysis of UK heat futures Eyre and Baruah (2014) noted the need for alternative scenarios which together spanned a broad uncertainty space. Using a combination of expert judgement and infrastructure modelling, Eyre and Baruah devised contrasting combinations of some key

sociotechnical variables, spanning not just the energy system but also wider socio-economic uncertainties. Like others, they recommended that in a context of high-level uncertainties, emerging path dependencies and prospective lock-ins and lock-outs, policy should be aimed at opening-up options and diversifying risk – suggesting a combination of more established and more emergent innovations.

Conclusions

Verbong and Loorbach (2012) noted a shift in energy transition dynamics from futurology, scenarios and visions, to a material phase characterised by massive actual (and anticipated) investments in infrastructure. With greater interests at stake, governments are increasingly concerned to derive economic benefit from energy and climate policy. In the UK and elsewhere, focus has turned increasingly to ‘industrial strategy’ and ‘clean growth’ as a driver of energy policy. The provisional UK Industrial Strategy has a list of energy innovation priorities: smart systems, electric vehicles, battery storage technologies and hydrogen systems (BEIS, 2017).

A UK Parliament committee has expressed concern for the kinds of decision-making involved here: an emphasis on ‘picking winners’ through sector-specific initiatives and deals, rather than an overarching approach to societal problems (HoC, 2017). In the meantime, more immediate policy priorities – related to buildings insulation, energy efficiency and shorter term measures to reduce transport sector emissions – have been neglected (CCC, 2017; UKERC / CIED, 2017).

The same parliamentary committee noted the risk, associated with industrial strategy based policy-making, that proposals will tend to reflect incumbents’ interests, given the implicit biases involved (HoC, 2017). Kemp (2011) also noted that information asymmetries and policy capture can result in narrow, interest based policy and regulation. Yet this is not just a danger in policymakers’ relations with incumbent interests – it applies also to niche- and disruptive-based interests.

Energy systems are undergoing substantial changes. In a context of heightened ambitions and urgency, however, there is a danger of privileging some dynamics above others. Kuzemko et al. (2016) distinguished between ‘forces for sustainability’ and ‘forces for continuity’, but this risks overlooking an important middle-ground in a spectrum of continuity and disruption, within which incumbents (and continuity-based innovation) are admitted a range of possible roles.

Preoccupation with disruptiveness as an energy transitions strategy risks marginalising and overlooking other important aspects of energy system change: mundane, incremental and continuity-based innovation, and possibilities for adapting existing systems. Ultimately, as many of the issues here can only be judged retrospectively, we need to be cautious, pragmatic and provisional in our assessments. As James Meadowcroft (2009) suggested, our ultimate concern should be solving societal problems rather than ‘tilting at systems’.

Theories matter because they shape analytical attention and the terms of research-policy debate. Now more than ever, independent research needs to be based on evidence and open-minded enquiry, rather than prefigured framings and received wisdoms. Given that we are all ‘boundedly rational’ and cognitively biased, this also means exposing our working assumptions and theories to contestation, counter-factual evidence and invited challenge, and to reflect a diversity of evidence and views in our prescriptions for policy. Adapting Van der Vleuten and Högselius (2012), there is a need for ‘symmetrically sceptical’ responses to both disruptive and continuity based narratives; by itself, the disruptive innovation narrative offers a very poor guide to research and policy.

Acknowledgements

The research supporting this paper was in-part undertaken within the UK Energy Research Centre, supported by the UK Research Councils under award EP/L024756/1. The author wishes to thank Charlie Wilson for comments on an earlier draft version of this article, and the contributors to the Disruptive Low Carbon Innovation Workshops (Wilson, 2017). The views expressed are the author's own.

Bibliography

- Abernathy, W. J. and K. B. Clark (1985) 'Innovation: Mapping the Winds of Creative Destruction', *Research Policy* 14, 3-22
- Anderson, P. and M. L. Tushman (1990) 'Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change', *Administrative Science Quarterly*, 35, 604-633
- BEIS (2017) *Building our Industrial Strategy*, Green Paper, Department of Business, Energy and Industrial Strategy, London
- Bergek, A., C. Berggren, T. Magnusson, M. Hobday (2013) 'Technological discontinuities and the challenge for incumbent firms: Destruction, disruption or creative accumulation', *Research Policy* 42 (6-7), 1210-1224
- Berggren, C., Magnusson, T. and Sushandoyo, D. (2015) 'Transition pathways revisited: Established firms as multi-level actors in the heavy vehicle industry' *Research Policy* 44 (5), 1017-1028
- Bowen, F. (2011) 'Carbon capture and storage as a corporate technology strategy challenge', *Energy Policy* 39 (5), 2256-2264
- Carbon Connect (2014) *Future Heat Part 1: Pathways for Heat: Low Carbon Heat for Buildings*, London, Policy Connect.
- Christensen, C. M. (1997) *The Innovator's Dilemma*, Boston MA, Harvard Business School Press
- Christensen, C. M., M. E. Raynor and R. McDonald (2015) 'What Is Disruptive Innovation?' *Harvard Business Review*, December 2015, 44-53
- CCC (2016) *Next Steps Next steps for UK heat policy*, London, Committee on Climate Change
- CCC (2017) *Meeting Carbon Budgets: Closing the policy gap*, 2017 Report to Parliament, London, Committee on Climate Change
- Danneels, E. (2004) 'Disruptive Technology Reconsidered: A Critique and Research Agenda', *Journal of Product Innovation Management*, 21, 246-258.
- DECC (2010) *Energy Trends: March 2010*, London: National Statistics and Department of Energy and Climate Change
- Edgerton, D. (2010) 'Innovation, Technology, or History: What is the Historiography of Technology About?', *Technology and Culture*, 51 (3), 680-697
- Edwards, P. N. (2003) 'Infrastructure and Modernity: Force, time, and social organization in the history of sociotechnical systems' in T. J. Misa, P. Brey, and A. Feenberg (eds.), *Modernity and Technology*, Cambridge, MA: MIT Press, 2003, 185-225
- Energy Institute (2017) *Energy Barometer 2017: Views from UK energy professionals*, London, Energy Institute
- Eyre, N. and P. Baruah (2014) *UK Energy Strategy Under Uncertainties: Uncertainties in Energy Demand in Residential Heating*, Working Paper, London, UK Energy Research Centre
- Franceschini, S. and F. Alkemade (2016) 'Non-disruptive regime changes: The case of competing energy efficient lighting trajectories' *Environmental Innovation and Societal Transitions* 21(Supplement C): 56-68
- Fri, R. W. (2003) 'The Role of Knowledge: Technological Innovation in the Energy System' *Energy Journal* 24 (4): 51-74
- Geels, F. W, Kern, F., Fuchs, G. Hinderer, N., Kungl, G., Mylan, J., Neukirch, M., Wassermann, S. (2016) 'The enactment of socio-technical transition pathways: A reformulated typology and a

comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990–2014)' *Research Policy* 45 (4): 896-913

Godin, B. (2016) 'Technological Innovation: On the Origins and Development of an Inclusive Concept, *Technology and Culture* 57 (3) 527-556

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

HoC (2017) *Industrial Strategy: First Review*, House of Commons Business, Energy and Industrial Strategy Committee, London

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

Högselius, P., Hommels, A., Kaijser, A. and Van der Vleuten, E. (eds.). *The Making of Europe's Critical Infrastructure: Common Connections and Shared Vulnerabilities*. Basingstoke and New York, Palgrave Macmillan

IEA (2016) *World Energy Outlook 2016*, Paris, International Energy Agency

IEA (2017) *Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations*, Paris, International Energy Agency

Kemp, R. (2011) 'Ten themes for eco-innovation policies in Europe', *Sapiens*, 4, 2, 1-19

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

Kuzemko, C. Lockwood, M., Mitchell, C. and Hoggett, R. (2016) 'Governing for sustainable energy system change: Politics, contexts and contingency' *Energy Research & Social Science* 12 (Supplement C): 96-105.

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

Lowes, R., B. Woodman and O. Fitch-Roy (2016) *Defining Incumbency: Incumbency: Considering the UK Heat Sector*, London, UK Energy Research Centre

Mäkitie, T., A. D. Andersen, J. Hanson, H. E. Normann and T. M. Thune (2016) *Established sectors expediting clean technology industries? The Norwegian oil and gas sector's influence on offshore wind power*, Working Papers on Innovation Studies, Centre for Technology, Innovation and Culture, University of Oslo

Markard, J. and V. H. Hoffmann (2016) 'Analysis of complementarities: Framework and examples from the energy transition' *Technological Forecasting and Social Change* 111 (Supplement C): 63-75.

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

McDowall W., E. Trutnevyte, J. Tomei and I. Keppo (2014) *UKERC Energy Systems Theme: Reflecting on Scenarios*, UKERC Working Paper, UK Energy Research Centre, London

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

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

Nightingale, P. and B. Martin (2004) 'The myth of the biotech revolution', *Trends in Biotechnology*, 22, 11, 564-569

Nightingale, P. and S. Mahdi (2005) 'The evolution of the pharmaceutical innovation process' in: Mazzucato, M. and Dosi, G. (eds.) *Knowledge Accumulation and Industry Evolution: the case of Pharma-Biotech*, Cambridge, Cambridge University Press.

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

Pacey, A. (1983) *The Culture of Technology*, Oxford, Basil Blackwell

- Paredis, E. (2011) 'Sustainability Transitions and the Nature of Technology', *Foundations of Science* 16, 2, 195-225
- Perrow, C. (2010) 'Comment on Mowery, Nelson and Martin', *Research Policy* 39, 8, 1030-1031.
- Policy Exchange (2016) *Too Hot to Handle? How to decarbonise domestic heating*, London, Policy Exchange
- PwC (2016) *Capturing value from disruption: Technology and innovation in an era of energy transformation*, London, PricewaterhouseCoopers
- Raven, R. (2007) 'Niche accumulation and hybridisation strategies in transition processes towards a sustainable energy system: An assessment of differences and pitfalls', *Energy Policy* 35, 4, 2390-2400
- Schot, J. and F. Geels (2008) 'Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy' *Technology Analysis and Strategic Management* 20, 537-554
- Schumpeter, J. A. (1994) [1942] *Capitalism, Socialism and Democracy*, London, Routledge
- Stenzel, T. and A. Frenzel (2008) 'Regulating technological change: The strategic reactions of utility companies towards subsidy policies in the German, Spanish and UK electricity markets', *Energy Policy* 36 (7): 2645-2657
- Suurs, R. and M. Hekkert (2012) 'Motors of Sustainable Innovation: Understanding transitions from a technological innovation systems perspective', in G. Verbong & D. Loorbach (eds.), *Governing the Energy Transition: Reality, Illusion or Necessity?* Abingdon: Routledge, 152-179
- Tushman, M. L. and P. Anderson (1986) Technological Discontinuities and Organizational Environments, *Administrative Science Quarterly* 31, 439-465
- Tushman, M. L. and L. Rosenkopf (1992) 'Organizational Determinants of Technological Change: Towards a Sociology of Technological Evolution', *Research in Organizational Behaviour* 14, 311-347
- UKERC / CIED (2017) *Unlocking Britain's First Fuel: The potential for energy savings in UK housing*, London, UK Energy Research Centre, and Brighton, the Centre for Innovation and Energy Demand.
- Unruh, G.C. (2002) 'Escaping carbon lock-in', *Energy Policy* 30, 4, 317-325
- Unruh, G.C. & J. Carrillo-Hermosilla, J. (2006) 'Globalizing carbon lock-in', *Energy Policy* 34, 10, 1185-1197
- Van de Ven, A, D. Polley, R. Garud, and S. Venkataraman (1999) *The Innovation Journey*, New York, Oxford University Press
- Van der Vleuten, E. and P. Högselius (2012) 'Resisting Change?: The transnational dynamics of European energy regimes', in G. Verbong & D. Loorbach (eds.) *Governing the Energy Transition: Reality, Illusion or Necessity?* Abingdon, Routledge, 75-100
- Verbong, G. and D. Loorbach (2012) 'Introduction' in G. Verbong & D. Loorbach (eds.) *Governing the Energy Transition: Reality, Illusion or Necessity?* Abingdon, Routledge, 1-23
- Voß, J-P, A. Smith and J. Grin (2009) 'Designing long-term policy: rethinking Transition Management', *Policy Sciences* 42, 4, 275—302
- Walker, W. (2000) 'Entrapment in Large Technology Systems: Institutional Commitment and Power Relations', *Research Policy* 29: 833-846
- Weiss, C. and W. Bonvillian (2009) *Structuring an Energy Technology Revolution*, Cambridge MA, MIT Press.
- Wilson, C. (2017) *Disruptive Low Carbon Innovation Workshops: Synthesis Report*, Norwich, Tyndall Centre for Climate Change and Future Earth. Norwich (Tyndall Working Paper 164)
- Wilson and Grubler (2014) 'Energy Technology Innovation' in A. Grubler and C. Wilson (eds.) *Energy Technology Innovation: Learning from Historical Successes and Failures*, Cambridge: Cambridge University Press
- Winkel, M. (2016) 'From optimisation to diversity: Changing scenarios of UK buildings heating' in D. Hawkey, J. Webb, D. McCrone, H. Lovell and M. Winkel, *Sustainable Urban Energy Systems*, London, Routledge / Earthscan
- Winkel, M. and J. Radcliffe (2014), 'The rise of accelerated energy innovation and its implications for sustainable innovation studies: a UK perspective', *Science and Technology Studies* 27, 1, 8-33