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Mapping the winds of whole system reconfiguration: Analysing low-carbon transformations across production, distribution and consumption in the UK electricity system (1990–2016)

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ABSTRACT

A founding assumption and aim of the sociotechnical approach to sustainability transitions was the need to develop frameworks to understand major systemic changes that would be required across the entire chain of production, distribution and consumption. However, most studies have so far focused on partial aspects of the entire chain, often a single, radical technology innovation. Therefore, since the founding ambition remains largely unrealized, the paper aims to contribute to transition scholarship by developing an approach for 'whole-system' analysis. As a second contribution, we argue that this broader unit of analysis calls for greater attention to the *architecture* of the system in terms of how constituent elements are linked to one another. To elaborate this point, we develop a reconfiguration approach, based on conceptual extensions to the multi-level perspective, analysing both techno-economic developments and socio-institutional developments. This approach draws attention to the multiplicity and interdependencies of change processes that constitute transitions, including incremental change, component substitution, symbiotic add-ons, knock-on effects and changes to the system architecture. A third contribution is to make an empirical whole-system analysis of the low-carbon reconfiguration of the UK electricity system between 1990 and 2016. This is important and timely, because it allows socio-technical transition approaches to 'speak' at the same empirical whole-system level that dominates current long-term, low-carbon (modelling) analysis and associated political and public debate. This consequently enables a demonstration of the added value of the whole-system reconfiguration approach. Our findings show that early reconfiguration of the UK electricity system was dominated by modular changes within the generation and consumption subsystems; and more recently, how these earlier changes have triggered a new focus on the whole system architecture, anticipating deeper changes to the linkages between the generation, network and consumption subsystems.

1. Introduction

Sociotechnical system innovation approaches, most notably the multi-level perspective (MLP) emerged as an important corrective to conventional approaches within innovation studies that had focused narrowly on individual technologies, firms and industries (Smith et al., 2010). They do so by conceiving of systems and regimes (such as those for electricity, mobility, agro-food) as comprised of multiple, heterogeneous 'elements' and understanding system transition as requiring major changes "along *the entire* production-consumption chain, its flows, its multi-level architecture, its institutions and structures, and – not least – the behaviour of the actors involved in it, from resource extraction to the final consumption of goods and services." (Weber and Hemmelskamp, 2005:1, *emphasis added*); this is described as a 'founding assumption in the literature on sustainability transitions" (Raven et al., 2016:164).

There has, however, been a disconnect between these calls for whole system transition and most of the studies that have been undertaken within this framing. For example, previous studies of the electricity transition (the empirical focus of this paper) have taken electricity *generation* as their unit of analysis, focusing mostly on single green niche-innovations such as solar-PV, offshore wind, onshore wind, biomass (e.g. Kern et al., 2014; Smith et al., 2014) with some studies also focusing on regime technologies such as coal, gas, and nuclear power (e.g. Geels et al., 2016). In a largely separate literature there has also been attention to a range of electricity *consuming* practices in domestic spaces, including laundry, eating, lighting etc. (e.g. Shove, 2003; Mylan, 2015; Monreal Clark et al., 2015). Until recently, electricity

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distribution has largely been ignored, although some studies are now emerging in the context of grid extensions and the incorporation of ICTs to create smart grids and meters (e.g. Pollitt and Bialek, 2008; Andersen, 2014).

This uneven and fragmented analysis of electricity may be problematic because the electricity system *does* form one large, integrated socio-technical system, because production and consumption of electricity need to be balanced in real-time to prevent black-outs. Various upstream inputs (coal, gas, nuclear, biomass, wind) are transformed into a single homogenous product (electricity), which may be used for many different end-uses. The importance of adopting a whole system approach to energy transition is increasingly recognised in policy, business and academic engineering communities (RAE, 2015; Energy UK, 2016; DECC, 2015). For these communities, whole system refers to a new focus that takes account of all technologies that comprise a system and the flows of energy, materials and information that link them together, sometimes including new and emerging flows across existing systems. Our socio-technical approach builds on this: we start with the system comprising production, distribution and consumption (of electricity), but deviate from the engineering perspective by also including analysis of actors and institutions, which is critical for understanding the interplay of stability and change during transition via whole system reconfiguration. We return to issues of system boundaries below.

We aim to make a contribution to debates about system transition by proposing a comprehensive unit of analysis, which not only spans generation, distribution and consumption, but also looks more precisely at the *architecture* of the configuration of elements. We hypothesise that this architecture differs for electricity systems, mobility systems, agro-food systems and heating systems, and that these differences have implications for transition dynamics. One important specificity of the incumbent electricity system is that supply and demand are separated via an electricity *network subsystem*, which has acted as a 'buffer', meaning that the electricity *generation subsystem* operates relatively independently from the electricity *consumption subsystem.* This perhaps explains why existing studies have typically focused on *either* generation or consumption.

So, while we generally agree with Sustainable Production and Consumption (SCP) research (Lebel and Lorek, 2008; McMeekin and Southerton, 2012; Geels et al., 2015) about the importance to look at both production and consumption, it should not be assumed that production and consumption always have very strong and direct interactions. Instead, we suggest that these interactions should be studied as an empirical matter and analysed in terms of the architecture of the configuration in different systems (electricity, agro-food, mobility).

The importance of specifying the unit of analysis, i.e. demarcating *what* system is studied as being in transition, is not an innocent choice because it is likely to shape how transitions are understood. Meadowcroft, (2009:326), for example, argues that "the identification of precisely which systems are of interest, and what sort of transition they are to undergo, are far from trivial. Answers to these questions cannot simply be 'read off' from the character of the social structure—because there are many nested and overlapping 'societal sub-systems' undergoing different types of inter-linked and overlapping 'transitions'"

In the context of this debate, the paper aims to make three interrelated contributions. First, we aim to broaden the unit of analysis to the whole socio-technical system across production, distribution *and* consumption, thus reconnecting to the original orientation of the transition literature. This 'zooming out' strategy is important to go beyond the single innovation focus and to complement the tendency in the literature to 'zoom in' and focus on the micro-struggles, debates and contestations. Second, we suggest that this broader unit of analysis calls for greater attention to system architecture and how constituent elements are linked to one another. This, we argue, has implications for the basic understanding and imagery of transitions. Much of the socio-technical transitions literature (including the MLP) focuses on substitution, overthrow, and discontinuity as a result of the breakthrough of a radical niche-innovation. While such substitution-based transitions do sometimes happen (particularly in systems organised around a single core technology), we suggest that they are not the only transition pathway and perhaps not even the most prevalent one. We therefore suggest that whole system transition may be better understood with a different imagery, which we characterize as (gradual) *reconfiguration*. Some historical case studies of transitions through reconfiguration already exist (Berkers and Geels, 2011), but these mainly establish the phenomenon and focused primarily on gradual changes in technical components. Reconfiguration is also already acknowledged as one of four possible transition pathways (Geels and Schot, 2007) and as a fruitful position in the debate on Sustainable Consumption and Production (Geels et al., 2015). This paper aims to further develop a reconfiguration perspective for whole systems, focusing in particular on how system architecture influences reconfiguration dynamics *and* how reconfiguration can change the system architecture. The perspective also suggests that transitions may be based on multiple co-existing and/or interacting reconfiguration dynamics, rather than on a single point source niche innovation as in the conventional niche-regime substitution imagery. The third contribution is to make an empirical whole system analysis of the low-carbon reconfiguration of the UK electricity system. This is important and timely, because it allows socio-technical transition approaches to 'speak' at the same empirical whole system level that dominates long-term low-carbon (modelling) analysis and associated political and public debate. This consequently enables a demonstration of the added value of the whole system reconfiguration approach.

2. Towards whole system reconfigurational analysis

To elaborate the basic imagery of whole system reconfiguration, we start with the basic conceptual building blocks of socio-technical analysis in general and more specifically, the multi-level perspective (MLP). The MLP understands system transition at the level of large societal domains (such as mobility, electricity and agri-food) unfolding through interactions between niches, system-regimes and an exogenous landscape. Conventional MLP studies have conceptualised regimes as representing the semi-coherent set of heterogeneous elements against which niches struggle (Rip and Kemp, 1998; Geels, 2002). Smith et al. (2010: 441), for instance, propose the following definition: "Socio-technical regimes are structures constituted from a co-evolutionary accumulation and alignment of knowledge, investments, objects, infrastructures, values and norms that span the production-consumption divide". This definition fits well with earlier STS studies, which proposed that analysts should look at 'seamless webs' (Hughes, 1986) leading to depictions of systems of multiple elements, such as the one for electricity in Fig. 1 (Hofman et al., 2004).

We argue that it is time to move beyond the seamless web conceptualisation to one that pays closer attention to the architecture and linkages of system-regimes. To move beyond the notion that 'everything is linked to everything else', the literature on tight and loose coupling is useful. Weick (1976:3), for instance, defines loosely coupled systems as "a situation in which elements are responsive, but retain evidence of separateness and identity". This means that whole systems may consist of sub-systems, in which elements are interacting more with each other than with elements in other sub-systems. This is an empirical question with relevance for identifying the *architecture* of the overall system. As later sections will validate empirically, we suggest that the UK electricity system, which was subject to a major institutional overhaul in the 1990s, comprised three subsystems - generation, (distribution) network and consumption - which exhibit a high degree of distinctiveness in terms of technologies, actors and institutions (Fig. 2).

This conceptualization is relevant for a system reconfiguration perspective, because it implies a two-way association between system

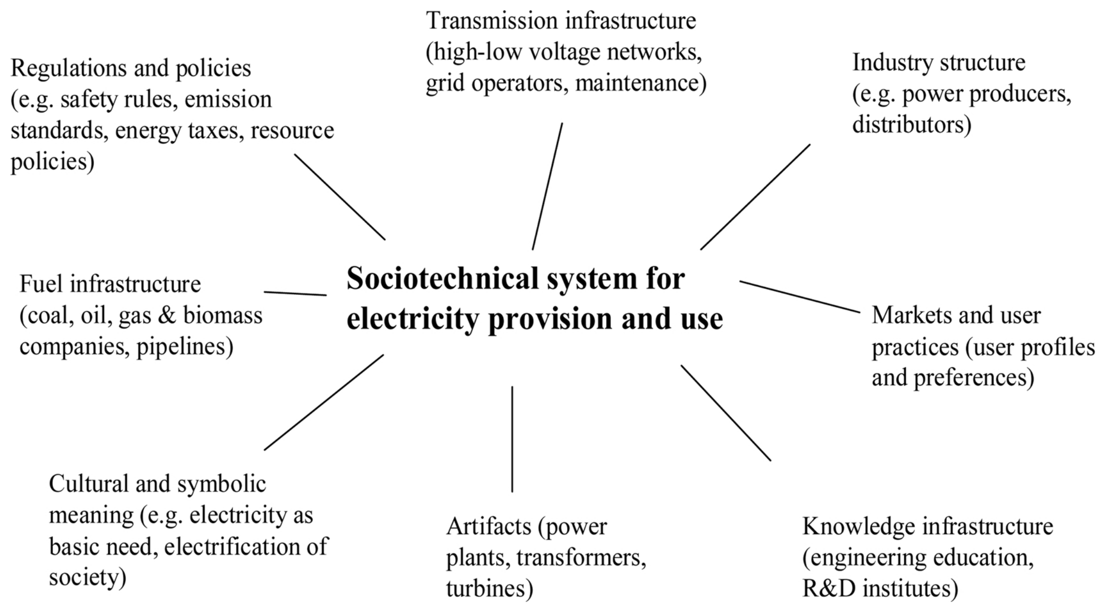

Fig. 1. Sociotechnical system for electricity provision and use (Hofman et al., 2004: 345).

architecture and low-carbon reconfiguration. On the one hand, the three sub-systems may experience relatively *autonomous and distinctive* change processes; on the other hand, as reconfiguration progresses, linkages between the subsystems may change, leading to a *new whole-system architecture*. Also, rather than 'tilting at systems' (Meadowcroft, 2009), we suggest that whole systems may experience different *types of reconfiguration dynamic*, which can all make contributions to low-carbon goals, including: incremental change, component substitution, symbiotic add-ons, knock-on effects and changes to the system architecture. Fig. 3 schematically positions these dynamics in the MLP's three layer categories, while also distinguishing possible interactions between three sub-systems. These elaborations show how a reconfiguration perspective differs from the conventional niche-regime overthrow imagery.

As an initial step towards systematizing different types of reconfiguration dynamics in whole systems, we draw on the typology by Henderson and Clark (1990), who aimed to go beyond the conventional distinction of incremental and radical innovation (which is similar to the dominant MLP imagery of regime vs. niche innovation). Their typology combined two axes distinguishing between the extent to which core concepts underpinning components of a system are overturned and the extent to which linkages connecting system components change

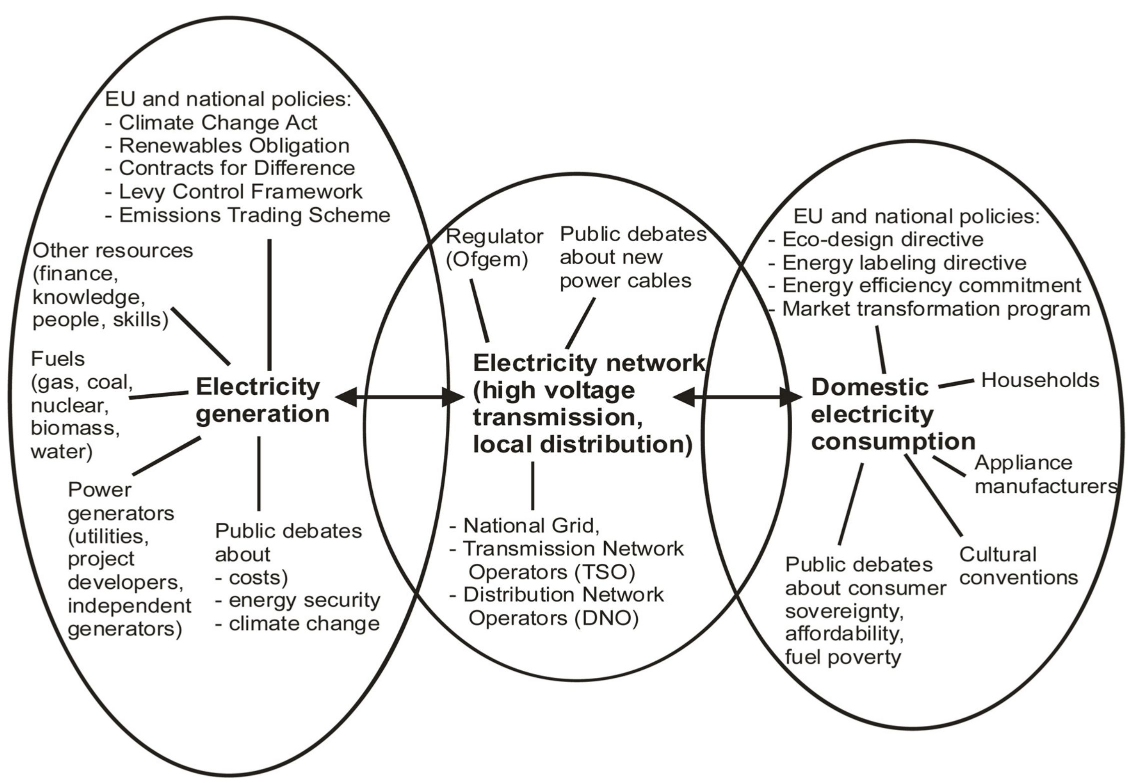

Fig. 2. Schematic representation of the electricity socio-technical system.

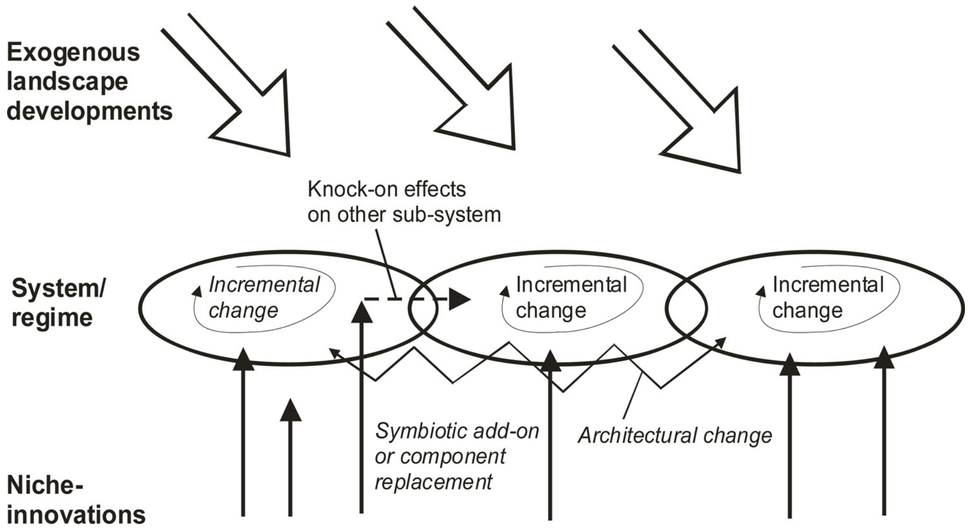

Fig. 3. Multiple niche-innovations and sub-systems in elaborated multi-level perspective.

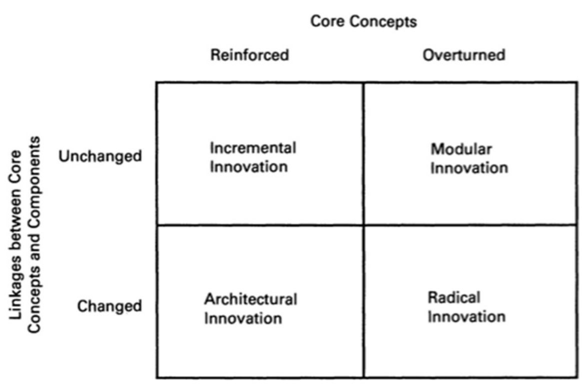

Fig. 4. A framework for defining innovation (Henderson and Clark, 1990: 12).

(Fig. 4).

Although Henderson and Clark applied their typology to products (consisting of multiple components), we think it can also be applied to broader systems. 'Incremental innovation' involves small improvements in technology that do not affect the dominant design or architecture (Anderson and Tushman, 1990). 'Radical innovation' in their typology involves wholesale change to both the core concepts underpinning system components and the linkages between components. 'Architectural innovation' is 'the reconfiguration of an established system to link together *existing* components in a new way' (Henderson and Clark, 1990:12, *emphasis added*). Finally, 'modular innovation' involves change in one component of a system, with little or no change to how components are linked (Baldwin and Clark, 1997).

We will use this typology as a guiding conceptualisation for our analysis of electricity system reconfiguration, but suggest it may need to be elaborated in two ways. First, the typology is static and focuses on categorizing single instances of innovation, whereas whole system transition involves multiple changes that unfold over several decades and may involve knock-on effects or innovation cascades. In this respect, our concerns with temporal processes recalls the transilience framework of Abernathy and Clark (1985), which used a similar typology to 'map the winds of creative destruction' in the automobile industry. Second, the typology may prove too dichotomous to capture all relevant reconfiguration dynamics, suggesting a need for intermediate categories (e.g. to capture combinatorial innovations where new and old technologies are hybridised). We will revisit these issues in the analysis and discussion section.

Our 'zooming out' strategy to whole systems has a potential trade-off, namely the difficulty of paying simultaneous attention to micro-struggles, changing perceptions, individual strategies, or specific debates. Misa (1994) described this trade-off as follows: "macro studies tend to abstract from individual case studies, to impute rationality on actor's behalf or posit functionality for their actions, and to be order driven. (…) Micro studies tend to focus solely on case studies, to refute rationality (…) and functionality, and be disorder-respecting." While this paper does not claim to resolve this dilemma, we do try to find a middle way that accommodates some degree of agency, struggle and non-linearity, while maintaining a focus on whole systems. We do this by using the distinction between tangible techno-economic and more intangible socio-institutional dimensions (Geels, 2004). The *techno-economic* dimension of whole systems is the dominant approach for national agencies such as the UK Committee on Climate Change and international bodies such as the Intergovernmental Panel for Climate Change. Based on technology learning curves and market prices, these analyses typically produce relatively linear pathways for transition. In contrast, sociotechnical studies also focus on the *socio-institutional* dimension, which is constituted by the semi-coherent set of rules and (regulative, normative and cultural-cognitive) institutions that shape the actions, interpretations, and identities of actors and social groups, who reproduce and maintain the system elements. Our approach is based on the recursive interaction between the techno-economic and socio-institutional dimensions.

Finally, we need a conceptual language that moves beyond the conventional transition image of long periods of socio-institutional stability, punctuated by abrupt moments of socio-institutional overthrow. Institutional scholars from beyond the sustainability transitions debate have, over the last decade, started to elaborate a new language that seems promising. Distinguishing between process and outcome, these approaches (e.g. Streeck and Thelen, 2005) characterise several types of gradual change process: *displacement, exhaustion, layering, conversion* and *drift* to add to the standard language of *reproduction* versus *overthrow*. Innovation scholars have started to make use of these ideas for studying system innovation (Dolata, 2009; Geels et al., 2016) and we will build on these earlier studies in our analysis of socio-institutional reconfiguration dynamics.

On the other hand, we also want to capture instances where actors were purposively attempting to actively disrupt, modify, create and maintain socio-institutional arrangements. This connects with the literature on institutional work (Lawrence and Suddaby, 2006), which understands institutional change as a matter of agents working on the institutional arrangements that constrain and enable their own actions (which is also similar to Garud et al's (2010) conception of socio-technical path creation). Again, the account is more complex than conventional transition conceptualisations that portray a simple struggle between incumbent actors seeking to maintain and defend institutions and niche actors seeking to create new institutions to protect or empower new niches (Smith and Raven, 2012). Incumbents do engage in defensive institutional work (Maguire and Hardy, 2009), but are also involved in creating new institutions in support of low-carbon futures (Smink et al., 2015).

Combining the conceptual language of gradualist institutional change with a focus on actors' institutional work may be a promising avenue for further developing a reconfiguration approach to socio-technical system transition. Pursuing this would draw attention to instances where incumbent firms reorient towards new pathways (Bergek et al., 2013; Berggren et al., 2015) and provide a finer grained understanding of heterogeneity, conflict and tensions within subregimes (Jørgensen, 2012; Fuenfschilling and Truffer, 2014) rather than viewing them as entirely coherent and monolithic until overthrown.

3. A methodology for whole system reconfigurational analysis

This paper uses a case study approach to explore the dynamics of whole system reconfiguration. Case studies offer opportunities for in-depth analysis and a single case design allows an even deeper level of investigation into a given phenomenon (Siggelkow, 2007; Flyvbjerg, 2006). This is especially suitable for our aim to question current orthodoxy around transition imageries by providing a first exemplification of a broader unit of analysis covering the three subsystems of production, distribution *and* consumption and paying greater analytical attention to how architecture effects reconfiguration processes. Studying the electricity system is particularly interesting because it is this system that has achieved the most pronounced low-carbon progress in the UK (Fig. 5). As the quote above from Meadowcroft (2009) suggested, specifying system boundaries to establish an appropriate unit of analysis for studying transitions is inevitably a matter of judgement and choice. In this study, we demarcated the system by placing its boundary around UK household electricity consumption (which by definition is nationally bounded) and the connected systems (UK and international) that account for how that electricity is generated, distributed to UK homes and used to power appliances developed and sold globally. While this bounding can be contested, we believe it to be an appropriate unit of analysis for starting to conceptualize whole system reconfiguration because: 1) the system draws some coherence through the territorial focus on domestic consumption; 2) it relaxes the territorial bounding for how that consumption is provisioned (including international actors) and how all three subsystems are governed (e.g. supranational governance and landscape developments). We return to the issue of units of analysis in the conclusion to reflect on how initial system boundaries (established in 1990) may become porous, leading to cross-system linkages as transitions unfold (e.g. new linkages between electricity and automobility).

The empirical research was guided by conventional analytical categories – niches and regimes and landscape pressures - from the MLP

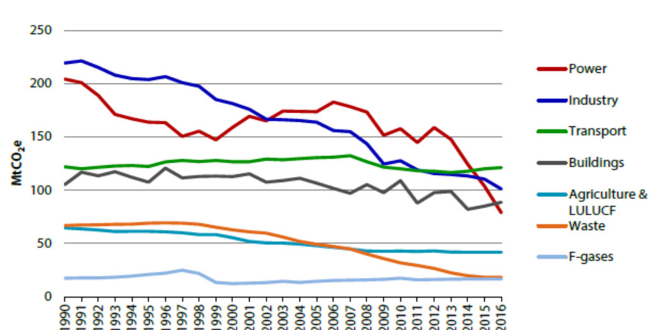

Fig. 5. UK emission reductions by sector, 1990–2016 (CCC, 2017:26).

and disaggregates the *single* sectoral trend (Fig. 5) to reveal *multiple* changes across the three subsystems and associated niche innovations. We chose a temporal frame for the study to start in 1990, after the whole system had been overhauled under privatisation and liberalisation policies, ending in 2016, just after the UK government 'energy policy reset'.

Quantitative information for 'tangible' techno-economic system elements was collected from energy statistics available from DECC (Department of Energy and Climate Change) and from reports by the Committee on Climate Change. Qualitative data and interpretations of socio-institutional developments drew on secondary sources (books, articles, reports) and primary sources (White Papers, policy documents, newspapers, company annual reports, industry journals). The heterogeneous data were integrated to construct an interpretive analysis.

As outlined in section 2, we mainly adopted a "zooming out" strategy, focusing on overarching socio-institutional developments, but we also aimed to tackle Misa's trade off by giving some attention to agency (e.g. struggle, conflict, search, learning, negotiation). After briefly describing the main landscape pressures shaping UK electricity during the period, we present four periods, which correspond to shifts in the interplay between modular and architectural changes (which are also related to significant shifts in system governance and shifts in the relative strength of different landscape pressures).

4. UK Domestic electricity system reconfiguration 1990-2015

4.1. Landscape pressures

The UK electricity system has been affected by several exogenous landscape developments over the period 1990-2015:

1 The continuing gradual shift towards an *information society* with the proliferation of ICT-devices in households and possibilities for ICT-enabled smart grids.
2 The *further electrification of society*, which has seen the increasing introduction of electric appliances for a growing number of household practices, and the potential for the electrification of heating and transport (e.g. electric heat pumps, electric cars).
3 Persistent embedding of *consumer culture* with deeply entrenched *cultural conventions* (e.g. for convenience, cleanliness, entertainment) affecting consumer expectations and domestic electricity consuming practices.
4 *Neo-liberal ideology* led to privatisation and liberalization of the UK electricity system in the 1990s and the adoption of a hands-off policy style. Low electricity costs became a crucial goal for both utilities and policymakers.
5 The global issue of *climate change* gained political prominence since 1997, when Labour won the election, but decreased on the political agenda after 2010.
6 *Geo-political developments,* including *tensions* with Russia (since 2005) increasing the importance of energy security and *extensions* in terms of further European integrated market formation (e.g. interconnectors for electricity import / export), which may subsequently be challenged by Brexit outcomes.
7 The *financial-economic crisis* of 2007 and subsequent austerity, which affected electricity demand, investment in low carbon generation technologies and infrastructure, and magnified concerns about domestic energy prices.

Fluctuations in these landscape pressures interacted with endogenous changes at the niche and regime level shaping reconfiguration dynamics within the three sub-regimes and linkages between them. The subsequent analysis focuses on these changes in more detail.

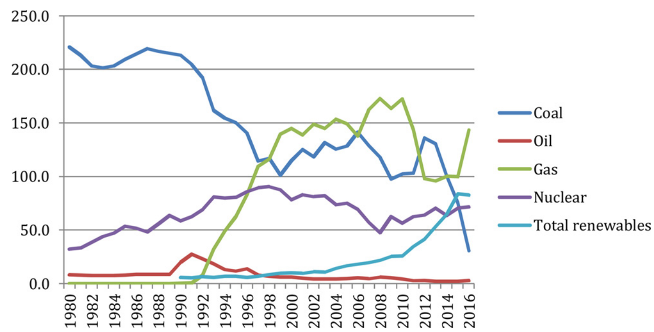

Fig. 6. UK electricity generation by fuel type, 1990–2016, in TWh (data from DUKES: Digest of UK Energy Statistics, https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes).

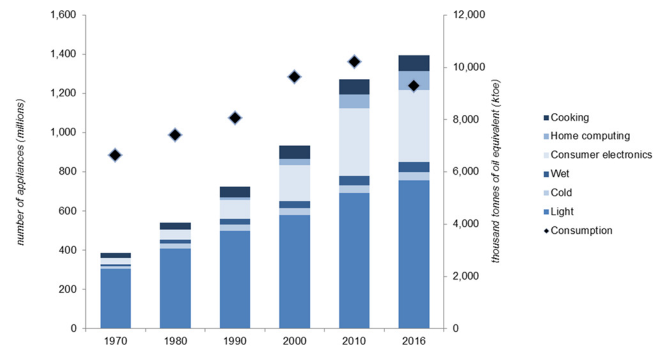

Fig. 8. Total number of electrical appliances owned by households and total domestic electricity consumption (right hand axis) Source; BEIS, 2017 table 3.04.

4.2. Neoliberal system architecture embedding and the emergence of climate change as a political issue: 1990-2002

4.2.1. Electricity generation

Neo-liberal ideology led to privatisation and liberalisation of the UK electricity generation industry through the 1990s. This entailed government stepping back and adopting a more ‘hands-off approach’, resulting in the ‘Big Six’ utilities and the creation of an independent energy regulator (Ofgem). The new governance style introduced competition and market-principles to the electricity system, with the specific aim to focus utilities on low costs (Pearson and Watson, 2012).

These changes stimulated a ‘dash for gas’ in the 1990s (Winskel, 2002), significantly substituting coal-powered generation, which was also facing European regulatory pressures. Nuclear generation also increased for most of the 1990s, but the run up to privatization had revealed its poor economic performance, and waste problems further undermined its cultural legitimacy (Verhees, 2012).

This technological switching (Fig. 6) was not initially driven by the climate change agenda; however, because gas and nuclear have lower carbon intensities than coal, the changes generated some CO2 emission reductions. Later in the period, climate change did start to emerge as a global political issue, especially with the 1997 Kyoto protocol, and the Labour Party making the issue a central component of its 1997 election campaign. With climate change gaining increasing attention also in public debates, various actors (project developers, utilities, landfill site operators, farmers) started to experiment with and install renewable generation technologies, especially onshore wind-farms, landfill gas and dedicated biomass plants (Fig. 7).

4.2.2. Electricity consumption

In the consumption sub-regime, ownership of electric appliances by UK households increased (Fig. 8), continuing longer-term trajectories of household electrification with further adoption of already existing

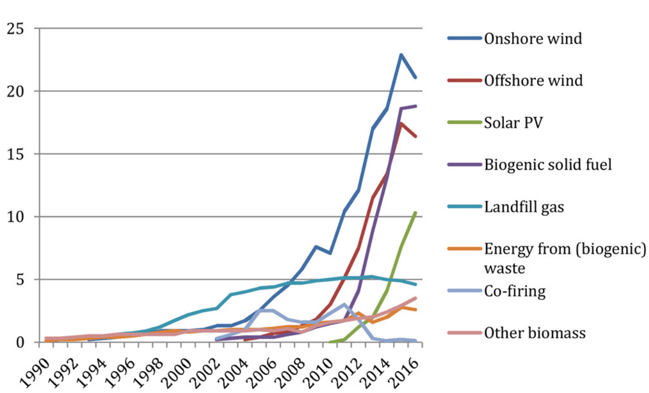

Fig. 7. UK power production from RETs, excluding hydro, in TWh, 1990–2016 (data from DUKES).

appliances (washing machines, freezers, dishwashers), and the introduction of new appliances (e.g. microwaves and the start of an explosion in new ICT and entertainment technologies). By the 1990s, electricity was a *taken-for-granted* background to modern life and hardly questioned as a form of *in*conspicuous consumption (Shove and Warde, 2002).

Instead, widely shared cultural conventions (such as comfort, cleanliness, convenience, freshness, connectivity and entertainment) shaped consumer expectations and domestic behaviour (Shove, 2003), often giving rise to increased demand for electricity. For example, Gatley et al (2014) documented the trend towards ‘convenience eating’, associated with interdependent innovations in ready meals, freezers and microwaves (Hand and Shove, 2007).

In our view, these domestic cultural conventions strongly aligned with the dominant beliefs and guiding principles of international appliance manufacturers and retailers oriented towards developing and selling cheaper products with more functionalities on the basis of which they competed in the market place.

However, incumbent firms in the domestic electricity consumption regime also started to incorporate energy efficiency as an *additional* consideration during the 1990s, which led to some re-orientation of industry strategies and beliefs towards incremental efficiency innovation. The industry association, AMDEA, initially resisted EU efforts for mandatory energy efficiency standards (Newell and Paterson, 1998: 684). It believed that energy efficiency was a marginal issue for consumers and argued that energy labels would therefore only impose costs on manufacturers (Toke, 2000). But, by 1996, “AMDEA had become convinced that they needed to protect their interests by acting within, rather than against the energy efficiency lobby. Their world view had changed.” (Toke, 2000). As such, firms became increasingly compliant and retailers started to become “adept at selling the benefits of more efficient products to consumers” (Winward et al., 1998).

“Cold appliances” showed the earliest efficiency improvements, with fridges using 27% less electricity in 2000 than in 1990 (DTI, 2001). Similar efforts at incremental efficiency innovation gradually spread across the global appliance-manufacturing sector (see Fig. 9). However, the UK Government’s compliance-only approach to EU Energy Label and minimum efficiency standards involved minimal effort to raise public awareness, which meant the UK experienced a slow rate of market transformation (compared to other European countries) (Boardman, 2004).

There were also more radical niche innovations aiming to reduce electricity consumption in the lighting category. Compact fluorescent lighting (CFLs) and halogens, with significantly better energy efficiency compared to incandescent lighting were already commercially available by the 1990s, but household adoption was slow to take off.

The slow uptake was shaped by the higher relative purchase price of CFLs (although full lifetime costs were lower (Menanteau and Lefebvre, 2000)), but also because cheaper CFLs imported from Chinese firms

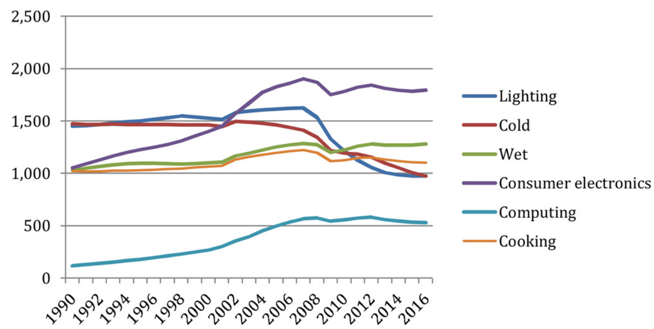

Fig. 9. Electricity consumption in UK households by appliance, in ktoe (graph compiled from data tables at https://www.gov.uk/government/statistics/energy-consumption-in-the-uk).

(Khan and Abas, 2011) jarred with consumer expectations about desirable 'qualities' of light because they were perceived as 'cold', unreliable, slow to become bright, unattractively shaped and incompatible with existing fittings (Wall and Crosbie, 2009; Monreal Clark et al., 2015). Government support for low energy lighting initially involved information campaigns and small-scale give-aways, but these had very little effect on voluntary acquisition (Martinot and Borg, 1998).

4.2.3. Electricity network

The network sub-regime was also reconfigured with 1990s privatization, with the transmission grid managed by a single system operator, which later became National Grid and three regional Transmission Network Operators (TNOs). The local distribution system was organized into 14 regional area monopolies, run by 14 Distribution Network Operators (DNOs), working to a standard operational model: managing one-directional and passive (or 'un-smart', Lockwood, 2013b) networks, involving no direct interaction with domestic users and minimal monitoring of the network.

Since 1998, Ofgem's regulatory remit was to "protect the interests of existing and future consumers", which included oversight of network actors, implementation and monitoring of regulations (such as price controls), and approval of network investment plans. Heavily informed by neo-liberal economic beliefs, competition was seen as the best way to drive prices down and serve consumer interests via price control regulation (RPI-X) and infrastructure investment intended to induce efficiency gains (Jamasb and Pollitt, 2007). The focus on efficiency and cost reduction hindered innovation as it stimulated TNOs and DNOs to 'sweat the assets' (by postponing network investments) and downscale R&D investments (Pollitt and Bialek, 2008).

4.2.4. System reconfiguration summary

Based on the above description, we suggest that significant socio-institutional upheaval at the start of the period, especially for the generation and network regimes, changed actor roles and identities across the sub-regimes, establishing a new system architecture and mode of governance. Technology changes in the generation regime (fuel switch) and consumption regime (incremental efficiency improvement) proceeded with a high degree of within-regime modularity and the overarching system architecture settled into a pattern of only loosely coupled linkages (principally via the price mechanism) across sub-regimes. Climate change emerged as a political issue from 1997, but had relatively little impact on actual low carbon innovation (because the dash-for-gas, nuclear expansion and appliance efficiency were shaped more by cost and efficiency issues).

4.3. Architectural reproduction and the emergence of radical climate policy: 2003-2009

4.3.1. Electricity generation

The 2003 Energy White Paper established a new 60% carbon emission reduction target, and was initially envisaged to operate within the existing market-based neo-liberal policy style, emphasising emissions trading as the main policy instrument. But the radical 2008 Climate Change Act (which introduced 80% reduction targets for 2050) marked a shift towards increased interventionism (Pearson and Watson, 2012; Lockwood, 2013a), in a context of broad political and societal support (Carter and Jacobs, 2014). New policy actors were created: the Department of Energy and Climate Change (DECC) and the independent Committee on Climate Change (CCC), with responsibilities for monitoring progress against climate change targets and advising the government accordingly.

The general strengthening of political governance provided impetus for the deployment of radical RET innovations, which was also shaped by contrasting and fluctuating levels of socio-political legitimacy and relative prices.

Onshore wind deployment accelerated first, with incumbent utilities incorporating wind farms into their generation technology mixes, leaving the dominant generation sub-regime (large-scale, centralised) architecture intact. But, it also started to face increasingly negative public opinion and opposition because of problems with planning permission and poor consultations, limited support from NGOs and concerns about intrusions on the countryside (Toke et al., 2008).

Offshore wind deployment was slower, largely involving experimentation, demonstration and learning, but this led to "a highly networked coalition of powerful and resourceful actors emerg[ing] which boosted the credibility of and channelled resources to offshore wind. Formal networks centre[d] around key public organisations as well as incumbent energy regime actors" (Kern et al., 2014).

Biopower remained a fragmented niche, deployed outside of the dominant incumbent-led regime; nevertheless as a technology that could convert waste into continuous (rather than intermittent) power, bio-power continued receive some support.

The use of coal and gas fluctuated with swings in political support, regulatory pressures and relative prices. Initially, coal was anticipated to decline further, but subsequently envisaged to have a role with the incorporation of carbon capture and storage (CCS), supported by a £1 billion subsidy, although most of the corporate activity on CCS "focused on basic scientific research and lobbying governments for subsidies and support rather than investments needed to deploy the technology on a commercial scale" (Bowen, 2011:2256). Nuclear was initially viewed as too expensive, but later experienced a policy renaissance in 2008 with plans for the construction of at least eight nuclear power plants by 2025. The renewed support for coal and nuclear emerged in part as a response to new landscape pressures raising concerns about energy security (for imported gas), despite both technologies being subject to social and political legitimacy problems (Verhees, 2012).

4.3.2. Electricity consumption

Continued landscape pressures in the form of shifts to an information society and electrification of the home led to: 1) the continued diffusion of all appliances, especially computing and consumer electronic entertainment technologies; 2) multiple ownership within single households of some appliances (e.g. fridges, TVs, computers); 3) many new types of small appliance (e.g. bread machines and juicers); 4) more power hungry appliances, through incorporation of new functions (e.g. ice-makers for fridges) or increases in their size (e.g. American fridges, TV screens); 6) decreases in manufacturing cost for electrical appliances, leading to price reductions and therefore increased affordability for consumers (EST, 2011; Van Buskirk et al., 2014).

In addition, changes in domestic practices led to a intensification of appliance use which meant, for example: 1) cold storage of more foods and drinks because consumers associated chilled goods with expectations of freshness and naturalness (e.g. orange juice, Foster et al., 2012); 2) rising expectations for enhanced standards of home entertainment and for digital connectivity fuelled the diffusion of larger, internet-connected entertainment and computing technologies (Crosbie, 2008), also with growing 'multi-tasking' in domestic practices (i.e. the simultaneous use of electricity-using devices such as TVs, mobile phones, tablets etc.) (Pantzar and Shove, 2010).

Despite these trends, domestic electricity consumption plateaued from 2005, because of the continuing gains achieved through further energy efficiency innovation. During this period, international appliance manufacturers had internalised energy efficiency into their innovation routines to sell more, but also more efficient, appliances. The overarching policy approach during the period continued to be shaped by EU regulatory frameworks (EU Energy Label and minimum efficiency standards), extending the scope for a wider range of products, but with the UK continuing to be a passive complier (Evrard, 2011).

The more radical innovations in lighting continued to face low adoption rates because of negative consumer perceptions created in the previous period. Earlier campaigns were expanded, with ever more generous give-away programmes (in 2009, 182 million bulbs); so generous, in fact, that the programme was prohibited in 2010 amid fears that unsolicited light-bulbs were not being used (POSTnote, 2010). Finally, in 2009, the EU announced a phase out ban for incandescent bulbs, which was accelerated in the UK by a voluntary retailer-led phase-out by December 2011.

Smart meters started to receive serious attention in the 2000s, under the dominant neoliberal framing of competition (by making supplier switching easier) and cost reductions (removing the need for meter reading site visits). Early studies, such as Darby's (2006) report for Defra suggested smart meters could lead to 15% demand reduction. Further trials of smart meters started in 2007, alongside a period of technology standard negotiation, especially regarding the use of In-Home Displays (IHD), which would provide information to consumers about energy use and potentially alternative tariffs. The hope was that making electricity use visible would encourage consumers to use less. However, this triggered "a storm of opposition" (Darby, 2008), especially from utilities, because it would add costs and not offer many supply-side benefits. Without waiting for the outcomes of trials, the government mandated in 2009 the roll-out of 53 million smart meters, *with* IHDs, by 2020 for all households and small businesses, at an estimated cost of £10.927 billion.

4.3.3. Electricity network

Since the early 2000s, the rise of climate change on the policy agenda led to increasing pressures on Ofgem with 1) the 2004 Energy Act leading to Ofgem having 'sustainable development' as a secondary statutory duty, although this was *layered* on top of the old remit instead of being internalized by the organization; and 2) the establishment of an Innovation Funding Incentive (IFI), which allowed DNOs to spend up to 0.5% of its revenue on R&D, although this led to limited actual implementation (Lockwood, 2013b). As such, in 2007, the Sustainable Development Commission questioned whether Ofgem had "kept pace with the climate change imperative and whether the government framework within which it operates is fit for the challenge of moving to a completely decarbonised electricity system by 2050″, and recommended changing Ofgem's primary duty to reflect this imperative (SDC, 2007: 6–8). Therefore, actual low carbon innovation was restricted to investments reacting to some pressures on the grid to accommodate new onshore wind locations and the offshore networks to accommodate the experimental offshore projects.

4.3.4. System reconfiguration summary

We suggest that this period largely reproduced the socio-institutional architecture of loosely coupled sub-regimes, despite the emergence of climate change as a political issue and a strengthening of government policy. Energy generators started to convert their activities to accommodate renewable technologies into their established large-scale, centralised operational logics. Appliance manufacturers continued to internalise efficiency into their innovation routines, but continued to sell more and a wider range of appliances and devices, which was strongly aligned to persistent cultural conventions and consumer expectations. The network sub-regime remained largely inert, beyond some investments to meet the need to accommodate new renewable generation locations. Climate change had emerged as a major landscape pressure, but through this period low carbon progress was achieved through modular changes *within* sub-regimes.

4.4. From modular innovation to knock-on effects and emerging architectural changes: 2010-2014

4.4.1. Electricity generation

The 2008 Climate Change Act and subsequent policy momentum continued to stimulate and accelerate the development of RET niches post 2010 (Fig. 7). On the basis of various incremental innovations, onshore wind continued to be the lowest cost (Gross et al., 2013) and most widely deployed RET. Offshore wind accelerated dramatically, because of the powerful advocacy coalition built earlier (Kern et al., 2014) and, despite remaining expensive, the UK became world leader for offshore deployment by 2014. Bio-power deployment also accelerated significantly. However, this was not on the basis of accumulated learning about small-scale dedicated biomass generation, but instead involved a switch to 'big biomass', based on converting pre-existing coal plants to generate electricity from imported wood pellets. These changes, which involved a fusing of previous regime and niche technologies benefitted from the Government's 2012 *UK Bioenergy Strategy* (DECC, 2012) because: 1) conversion came to be seen as more cost effective than new build dedicated biomass, indicating a preference for low cost over technical (and carbon) performance; 2) it fitted the government's overall preference for working with incumbents on established large-scale technologies rather than new entrants (Geels et al., 2016). As such, the onshore, offshore and biomass niches accelerated within a stable socio-institutional architecture.

However, these developments, fuelled by policy momentum and alignment with incumbent interests, started to experience growing opposition. Public attention to climate change started to decrease, leading politicians to realize that they were ahead of their voters, which resulted in a loss of cross-party support regarding climate policy (Lockwood, 2013a; Carter and Jacobs, 2014). Furthermore, the financial-economic crisis and the austerity response by government led to greater concerns about jobs, competitiveness and energy prices. In the autumn of 2013, the cost argument escalated into a political row over rising consumer bills, which in turn led to increasing opposition against green levies and subsidies.

More specifically, onshore, offshore and bio-power deployment met with distinct, niche specific countervailing pressures. Onshore wind was facing a crisis in socio-political legitimacy, despite low costs. Concerns about the landscape were voiced by powerful groups such as the Campaign to Protect Rural England and in an open letter (5 February 2012) by more than 100 Conservative MPs, who also demanded cuts in wind subsidies. Offshore wind was still facing cost pressures, which many commentators anticipated to be insurmountable, creating uncertainty and affecting investment decisions (Helm, 2012; CCC, 2013). By 2011, government launched an Offshore Wind Cost Reduction Task Force and in 2013 started lowering deployment targets, stating "actual deployment will depend on technology costs" (DECC, 2013: 8). Big biomass faced pressures because of increasing concerns about sustainability performance given the large-scale importation of wood pellets from North American forests. For example, in 2013, a coalition of NGOs released the report '*Dirtier than coal? Why government plans to burn trees are bad news for the planet*'. Furthermore, in the 2012 government strategy, bio-power was seen as fulfilling a "transitional role" with rapid expansion until 2020, followed by rapid decline in subsequent decades because of envisioned use of biomass in transport and heat domains.

In contrast to these large-scale RET developments, the fourth RET niche, solar-PV, was supported by a strong network of *new* entrants, including environmental NGOs, the construction industry, roofing contractors and the solar industry. The most decisive expression of this support was the highly visible public campaign in favour of the feed-in-tariff (FiT), which created pressure on policymakers. The government struck a political deal with pro-renewables backbenchers to support the government bill for nuclear in return for the introduction of a FiT (Smith et al., 2014). From 2010, the FiT triggered unanticipated interest and cultural enthusiasm, leading to rapid household adoption. Decreasing prices, stimulated through global competition and market expansion, also gave rise to wider cultural visions about the coming solar energy revolution and how it could transform energy systems towards decentralized production and active 'prosumers' (e.g. Barnham, 2014), ushering in a new system architecture. Policy-makers picked up on the enthusiasm: DECC's (2014a) *Solar PV Strategy* promoted a 'D3-agenda', in which solar-PV (with smart meters) could act as a stepping stone towards distributed generation, demand reduction, and demand response (see below).

In the midst of RET expansion, incumbent technologies experienced mixed support. UK government continued to envisage the nuclear renaissance, but encountered delays in reaching agreement with contractors. Coal plants continued to close or were converted to big biomass. Despite earlier investment plans, CCS demonstration failed to get off the ground, with the Committee on Climate Change (2014) highlighting "slow progress" and "little sign of urgency" (p. 127). Gas received increased support, with government expressing desires for 40 new plants by 2030 and with restrictions lifted on shale gas.

4.4.2. Electricity consumption

European regulatory frameworks continued to shape efficiency innovation, with further changes extending its reach across an even wider range of appliances. Implementation became increasingly tortuous with protracted technocratic debates about minimum efficiency thresholds (Cary and Benton, 2012) and label designs (Evrard, 2011). Occasional outburst of opposition emerged, for example the consumer group *Which*? encouraged consumers to quickly buy powerful vacuum cleaners while still available, and the issue was even used by UKIP as another reason for the UK to withdraw from Europe. Nevertheless, efficiency innovation continued across a range of appliances and the ban on incandescent lighting meant CFLs began diffusing rapidly, although the much more efficient LED lighting struggled to take off in the absence of any policy support and despite rapidly falling prices (Lott, 2014).

By the end of this period, AMDEA adopted more pronounced advocacy towards the efficiency agenda, lobbying UK government for *more* support: "A change in focus is required so that policies to reduce demand for electricity receive at least as much, if not more, attention than policies to encourage low carbon electricity generation" (AMDEA, 2014).

In addition to the technical efficiency agenda, UK policy-makers were increasingly interested in 'pro-environmental behaviour change' initiatives. For example, the Energy Saving Trust initiated information campaigns encouraging consumers to adopt greener habits and lifestyles, including switching off lights and reducing use of standby functions. These were mostly limited in their success, although a partial exception was the 'wash at 30′ campaign, led by Proctor and Gamble, Defra and the International Association for Soaps, Detergents and Maintenance Products, which aimed to reverse long held beliefs of consumers associating high temperature washing with socially acceptable expectations of hygiene and cleanliness (Mylan, 2017). While there was some evidence of households washing at lower temperatures, actual electricity demand reduction for laundry was minimal because clothes were washed more frequently in smaller loads and dried in tumble-dryers, driven by desires for greater convenience (Yates and Evans, 2016).

The roll out of smart meters, which intended to reach 100% of the population by 2020, struggled to take off and various controversies persisted (Sovacool et al., 2017). For example, energy companies tried to re-open the IHD debate, using the controversy about energy prices to call for a review of the costs of the smart-meter program and a replacement of expensive IHDs by cheaper apps on mobile phones or computers (*The Telegraph*, 2 February 2014). However, IHDs remained at the heart of the UK government vision because their functionality fitted with broader ambitions to use price incentives to change consumer behaviour (DECC, 2014b: 58). Indeed, by 2014 smart meters were increasingly viewed as a key enabling technology in visions of a smart electricity system, in conjunction with smart grids (see below).

4.4.3. Electricity network

New pressures on the network sub-regime started to emerge during the period because: 1) the creation of new wind farms in remote locations (e.g. Scottish islands, Welch coast, offshore) required the creation of new transmission networks, both onshore and offshore, to connect them to the grid; and 2) increasing electricity flows from Scotland and Wales (where most wind parks are situated) to England (where most electricity is used) required upgrading, extension and intensification of the onshore transmission grid; and 3) the need to have secure and continuous electricity supply (in the context of increasing volumes of intermittent generation) led to the building of *inter-connectors* that linked the UK to other countries. These projects required similar investment levels as those for renewable generation capacity. Between 2010 and 2013, £16 billion was invested in onshore and offshore transmission grids, and about £1 billion in inter-connection projects (CCC, 2013).

Decades of underinvestment meant the distribution network suffered from capacity problems. This placed constraints on the diffusion of *distributed generation* (e.g. community wind energy, small dedicated biomass plants and later, roof-top solar PV), because the distribution network was not designed to accommodate generation, and required two-way flows instead of traditional one-directional flows (from generators to users). Moreover, distributed generation developers needed to pay for network re-enforcement (as well as standard connection fees) when capacity was insufficient (Hall and Foxon, 2014).

Responding to previous criticisms, Ofgem therefore created a new Low-Carbon Network Fund (LCNF), which was an order of magnitude larger than IFI and allowed DNOs to bid for up to £500 million between 2010 and 2015, and a new RIIO-framework (Regulation = Incentives + Innovation + Outputs) in 2013. However, "the principles of Ofgem's approach to regulation, in which the main focus is on minimizing costs, maximizing efficiency, and avoiding the risk of stranded assets, remain largely the same. Innovation is seen as arising out of incentives for efficiency, along with some additional resourcing. The regulatory paradigm remains in force." (Lockwood, 2013b: 19). As such, DNOs remained largely resistant to change (Bolton and Foxon, 2015) and were slow to implement innovations because there was no articulated need from concrete clients (in contrast to TNOs and the transmission grid).

However, some new organisational networks, involving incumbents and ICT entrants, started to mobilise around the potential for smart grids. The Electricity Networks Strategy Group produced a high-level plan and a cost-benefit analysis for smart grids in the UK, followed by a 'route map' and then scenarios (ENSG, 2012). In 2011, DECC and Ofgem established a Smart Grids Forum (SGF), including representatives from the DNOs. Positive discourses, with visions of a transition to a low-carbon, smart electricity system (SGF, 2014), were accompanied by increasing R&D investment, but not by real-world implementation and roll-out.

A key aspect of this vision concerned significant organisational change for DNOs to become Distribution System Operators (DSOs), with much wider responsibilities as *active* managers of a smart distribution system; but DNOs were strongly locked in to their conventional role and associated routines, with major uncertainties concerning how value created from investment towards smart distribution would accrue to them (Hall and Foxon, 2014).

4.4.4. System reconfiguration summary

The majority of low carbon changes during this period were achieved through modular changes in the generation (with rapid acceleration of RETs) and consumption systems (further efficiency innovation), within a largely reproduced whole system architecture. However, we suggest that some changes started to reconfigure whole system linkages. First, network extensions changed the spatial configuration of the system to accommodate new RETs. Second and more radical, distributed generation (especially solar-PV) accelerated rapidly, altering the logic of generation-consumption linkages (prosumption). Finally, visions and experiments (in smart meters / grids) pointed towards a more radical transformation of electricity networks towards a smarter system *architecture*, which would entail significant changes in the logic of linkages between generation, network and consumption subsystems. But while *policy* momentum continued to stimulate deployment of low carbon innovations in this period, we observe that *political* and public support was beginning to decrease.

4.5. Fork in the Road - Architectural reshaping or stalled reconfiguration: 2015-?

4.5.1. Electricity generation

In 2015, The Paris COP21 agreement appeared to place greater pressure on countries to accelerate low carbon transitions. However, a month before that agreement, the newly elected Conservative Government announced an 'energy policy reset'. This signalled a change in governance orientation towards a more hands off role for government, with Amber Rudd, Secretary of State for Energy and Climate Change stating: "We want to see a competitive electricity market, with government out of the way as much as possible, by 2025."[1] In our view, the policy reset was, on the one hand, an outcome of growing social and political opposition to the diffusion of low carbon energy technologies as climate change receded as a dominant landscape pressure, replaced by cost concerns and supply security as major concerns in energy policy debates. On the other hand, it was an opportunity for the Conservative government to restore its preference for a neoliberal approach to electricity policy and support for incumbent firms.

It also signaled a new approach to electricity policy with plans to close down unabated coal generation by 2025. To fill the capacity gap, the government intended to expand new gas capacity (including shale gas), build new nuclear power plants, and increase renewable electricity (to 30% of total generation by 2020). Subsidies were slashed for onshore wind, bio-energy, solar-PV and CCS. While renewable deployment is likely to continue for the next few years because of pipeline commitments, we expect that this reduction of support (except for offshore wind) is likely to significantly reduce diffusion (see Figs. 6 and 7 for early signs of this). Shortly after the energy policy reset, the government struck a generous deal (£92.50 per MWh, for 35 years) with EDF for the Hinkley Point C nuclear plant, even then amidst significant controversy. Incumbents may also be encouraged towards a new dash for gas, but with the scrapping of CCS investment, it is difficult to envisage how this will stay within the Government's own carbon budgets.

4.5.2. Electricity consumption

Efficiency innovations in domestic appliances are likely to continue because international manufacturers will continue to sell to European markets under European efficiency policy frameworks, although Brexit may affect this.

The smart meter roll-out, whilst facing delays (Sovacool ; et al., 2017;) continued to strengthen visions about *demand-side response* (DSR), which promised the possibility of managing electricity demand to accommodate fluctuations in electricity supply. These visions hope that demand might be managed through a combination of smart meters and new kinds of electricity tariffs, such as time-of-use tariffs (in which the price of electricity varies according to the period of the day) or real-time ('dynamic') tariffs (in which prices vary every 10 min depending on interactions between supply and demand). DSR (in which demand follows supply) would not only change the linkages between demand and supply, but also entail a *reversal* of the current functional principle (in which supply follows demand). Anticipation of a future smart system also started to have further knock-on effects for appliance manufacturers, who are developing 'smart appliances', which "alter their behaviour in some way to benefit the wider electrical system" (Bilton et al., 2014:6).

4.5.3. Electricity network

Expansion of onshore and offshore transmission grids and international interconnectors continued after 2015. The growth of distributed generation also led to R&D and demonstration projects with smart grids, where the UK is one of Europe's leading countries (Gangale et al., 2017). Focusing on distribution networks, most projects address technical issues like bi-directional power flow management, sensors, automatic switches, power electronics devices, voltage and thermal constraints (Jenkins et al., 2015). In addition to the R&D from the previous period, there are also real-world demonstration projects, e.g. the Orkney islands active network management project (grid integration of high wind, wave and tidal energy loads), E.On MK2000 (smart homes and grids), and the Smart Hooky project (connecting monitoring nodes in 40 households in an Oxfordshire village to a smart hub at the distribution sub-station). These projects explore the viability of reconfiguring the grid towards bi-directional electricity flows and greater decentralisation, including new linkages between the consumption and network sub-regimes.

Additionally, there are pilot projects with energy storage, using home batteries provided by companies like Tesla, Powervault, Moixa and Sonnen. To further develop the UK energy storage market, the industry group Electricity Storage Network, established in 2008, spans boundaries in its interactions with manufacturers, network operators, policymakers and users (Vaughan, 2017). We suggest that the combination of DSR, distributed generation, smart grids, bi-directional flows and storage points to a significantly different system logic, with stronger linkages between the sub-systems. Such transformative visions are central to some government-associated reports (e.g., National Infrastructure Commission, Smart Power, 2017), but also experience tensions with other policies.

The capacity market (CM) policy, for instance, which is part of wider Electricity Market Reforms, has ambiguous effects in our view. CM policies were introduced in the early 2010s, leading to several rounds of auctions, starting in December 2014. To enhance supply security and address intermittency, CM pays power station owners, interconnectors, or providers of DSR or storage for the *availability* of electricity generation in agreed periods (i.e. back-up capacity). Although CM could, in principle, stimulate the system reconfiguration described in the previous paragraph, the chosen policy implementation parameters have, in fact, worked against this, leading Lockwood (2017: 17) to conclude that: "the protection of the existing system appears to have been a higher priority than the development of a new, more flexible and demand-side focused system". One problem is that the CM optimized on lowest cost and was not differentiated in terms of carbon intensity or flexibility. This meant that the great majority of capacity payments went to traditional energy companies for *existing* generation capacity, while DSR and storage received only about 1% of the capacity contracts.

[1] https://www.gov.uk/government/speeches/amber-rudds-speech-on-a-new-direction-for-uk-energy-policy

4.5.4. System reconfiguration summary

We suggest that the UK electricity system is approaching a major tipping point towards *a transformation* of the whole electricity system architecture, whereby subsystems become more tightly coupled and operate under significantly different system logics (e.g. two-way flows, distributed generation, intelligent load management, DSR, storage, back-up capacity, smart appliances). Sub-system boundaries are becoming more porous, as described above. However, recent policies like capacity markets and the ‘energy reset’ have ambiguous or constraining effects on electricity generation and grid developments. In our view, these policies seem to re-assert traditional institutional logics (hands off, least-cost, supply-side orientation) and a ‘working with incumbents’ pattern, which may hinder or delay a deeper whole system reconfiguration. There thus seems to be increasing tension between technological and institutional developments.

5. Analysis and discussion

The preceding empirical section provided a narrative account of how various reconfiguration dynamics in the whole sociotechnical system for UK domestic electricity led to a 50% fall in carbon emissions between 1990 and 2016 (CCC, 2016). We now return to the conceptual ideas presented in section 2 to further elaborate the significance of paying closer attention to whole system architecture in understanding the observed changes.

5.1. Modular and architectural whole system reconfiguration dynamics

To understand low-carbon system reconfiguration, we propose several elaborations of the original Henderson and Clark single technology typology. We retain the overarching logic of their two axes, but propose different and more differentiated categories, summarized in Fig. 10:

- *Modular incrementalism* retains the original typology logic and refers to incremental innovations with existing technologies, e.g. efficiency innovations in domestic appliances.
- *Modular substitution* differentiates the logic of the original typology to better account for three kinds of modular change in whole systems: 1) switching between existing regime technologies, e.g. gas for coal; 2) switching between new (niche) and old (regime) technologies, e.g. RETs for fossil fuels, CFL for incandescent lightbulb, and 3) hybridization of niche and regime technologies, e.g. coal-to-biomass conversion.

The original Henderson and Clark typology did not distinguish between *degrees* of architectural change, which appear significant in relation to our empirical assessment. We therefore elaborate architectural change into two categories:

- *Architectural stretching,* which involves incremental changes to system linkages, but with minimal change to the logic of the architecture, e.g. network expansion to accommodate new RET locations.
- *Architectural reshaping,* which involves more fundamental changes to the logic of linkages between the generation, network and consumption subsystems, e.g. smart grids, back-up capacity, storage, bidirectional flows, distributed generation, DSR.

As a mapping tool, this elaborated typology helps to characterise the *multiplicity* of major low carbon innovations in a typology that acknowledges the importance of system architecture (and therefore the possibility for modular changes *and* changes to system linkages) and how incremental or radical the innovations are compared to incumbent technologies.

However, we can also use the typology to characterise the *temporal pattern* of UK electricity system reconfiguration, based on the relative prominence of the different reconfiguration types during different time periods. Fig. 11 provides a summary depiction of the main developments in the three sub-regimes and their linkages.

Mapping the winds of whole system reconfiguration in a temporal pattern points to the significance of modular changes that accounted for the majority of low carbon progress over the whole period. While the generation, network and consumption subsystems functioned through different endogenous operational and innovation logics, they were nevertheless ‘held’ within a whole system because of the need to connect generation to consumption and to balance supply and demand. But, this loose inter-subregime coupling meant that *modular* low carbon innovations could be developed and deployed *within* subsystems, with negligible effects on the whole system architecture.

For the consumption sub-regime, the majority of low carbon progress was achieved through modular incremental efficiency innovations in domestic appliances. For the generation regime, low carbon progress came about through modular switching of less (gas, nuclear) for more (coal) carbon intensive technologies and more radical modular innovation of RETs for incumbent technologies.

		Core Concepts			
		Reinforced	Substituted		
Linkages (coupling) between system components	Unchanged	***Modular incrementalism*** -efficiency innovation in appliances	***Modular substitution*** ***Regime-regime switching*** between coal, gas, nuclear	***Niche-regime hybridisation*** coal - biomass conversion coal / biomass+CCS	***Niche-regime switching*** RETs for fossil fuels CFLs smart meters
	Changed	***Architectural stretching*** -grid expansion for offshore renewables and imports	***Architectural reshaping*** - smart grid, smart meters, smart appliances - storage - demand side response - electricity ‘pro-sumption’ (rooftop solar) and decentralized architecture		

Fig. 10. Mapping the winds of whole system reconfiguration.

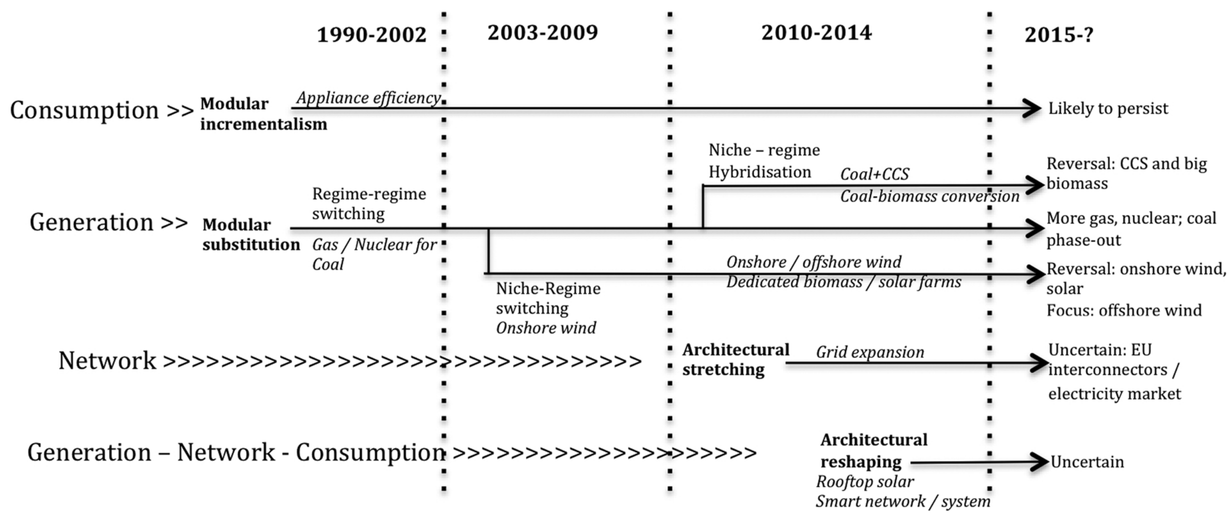

Fig. 11. Temporal pattern of low-carbon system reconfiguration.

The typology and temporal pattern also illuminate the *depth* and *breadth* of changes throughout the period. The right hand cells in Fig. 10 correspond to *deeper* changes, because core concepts are radically changed; and the bottom cells correspond to *broader* changes in the sense that they reach further across the three sub-regimes and involve changes to linkages that connect them. The UK case exhibits a pattern of system reconfiguration moving from incremental to deeper, more radical changes, and from localised to broader architectural changes. This suggests a preference for prioritizing least-cost (in the short term), minimal disruption options before those that entail more radical upheaval to the whole system architecture. To explore this pattern and preference further requires a deeper engagement with the socio-institutional dimensions constituting whole sociotechnical reconfiguration.

5.2. Socio-institutional whole system reconfiguration dynamics

In this section, we further develop the understanding of whole system reconfiguration by making three analytical points about socio-institutional stability and change. First, we explain how significant levels of decarbonisation were achieved through (sometimes radical) policy enactment, but with limited changes to deeper institutional logics. Second, we explain how incumbents worked with government to maintain the deeper institutional status quo of the three subregimes, while making compromises and changes to their activities to contribute to decarbonisation. Third, we suggest that while the recent period shows signs of architectural reshaping in technological dimensions (as shown in the previous section), socio-institutional changes appear to be lagging behind, which may have consequences for the deeper decarbonisation required to meet future carbon budgets.

With regard to *specific policies*, there have been many changes, contestations and struggles throughout the whole period. These changes mostly relate to non-linear learning processes and implementation experiences with *specific* innovations (e.g. onshore wind, solar-PV, bio-power, smart meters, lightbulbs). The strengthening and weakening of specific policies, which are typically developed in policy silos, help explain the relative speed of different modular changes.

However, with regard to underpinning institutional logics (e.g. roles, responsibilities, problem framings, goals), change processes have been more gradual after the institutional overhaul of the 1990s. Using Streeck and Thelen's (2005) conceptual repertoire, introduced in section 2, Table 1 provides a schematic summary of institutional reconfiguration for the three sub-regimes.

For the generation and consumption sub-regimes, this table shows that climate change was *layered* on top of post-liberalization, market-oriented arrangements, which subsequently led to increasing *conversion* of incumbent actors towards low carbon agendas. In the network sub-regime, this layering and conversion was largely unsuccessful, as the closed network of actors (Ofgem, National Grid, DNOs) remained committed to existing routines, mindsets and operating procedures.

Although institutional logics have not been disrupted or overhauled, significant decarbonisation has been achieved. While the neo-institutional literature often sees regulatory or policy change as relatively 'superficial' (e.g. Scott, 2008), this finding suggests that major low-carbon improvements can be achieved without radical change in institutional logics, provided that the policies provide sufficient (financial) incentives to stimulate the reorientation of incumbent actors.

This pattern of gradual policy change in the context of relatively stable institutional logics suits the interests of most incumbent organizations (e.g. utilities, appliance manufacturers, National Grid, DNOs, Ofgem), because it enables them to survive energy transitions (which in countries like Germany is more problematic). As such, our second analytical point is about how incumbents gradually adjust investment strategies and technical/operational capabilities, while maintaining their roles and identities in a stable whole system architecture.

Tight networks of incumbents and policy makers actively worked together to negotiate *compromises* (Oliver, 1991), which simultaneously maintained underpinning institutional logics, while gradually incorporating low carbon solutions. Much of this work focused at the level of individual technologies and practices within the generation and consumption subregimes. This indicates how incumbents displayed awareness, skill and reflexivity (Lawrence and Suddaby, 2006) in the face of fluctuating landscape pressures and emerging niches. As such, incumbents joined powerful advocacy networks for the promotion of different RETs that would fit with their stable roles and identities within a centralised, large-scale generation system. Similarly, appliance manufacturers eventually embraced the efficiency agenda (and via the trade association became a vocal advocate of it), because it could be adopted without disrupting existing product innovation and marketing strategies or the deeper institutional logics of consumer sovereignty and choice. In contrast, incumbents in the network subregime maintained institutions largely through *avoidance* or even *defiance* (Oliver, 1991) in the face of landscape pressures and unsuccessful attempts by government introduce new remits for incumbent actors.

Because of these strategies, the whole system architecture of three loosely couple subregimes remained largely intact in the first twenty years of our case (first and second period). However, our third analytical point concerns more recent developments since 2010 (third and fourth period), where there were signs that subsystem boundaries were becoming more porous, suggesting the emergence of a new phase of

Table 1
Socio-institutional developments for low carbon reconfiguration (text in italics refers to build up of new pressures with consequences for changes in the subsequent period).

	Generation subregime	Network subregime	Consumption subregime
1990-2002	**Reproduction:** of post-privatisation arrangements. Policy support for cost saving, competition – and the dash for gas (modular regime technology switching). *Growing advocacy for renewables as climate change becomes prominent in public and political arenas*	**Reproduction:** of post-privatisation arrangements and club governance. Network operators and regulator maintain beliefs, strategies and routines oriented towards efficiency, competition and cost – little on innovation.	**(Incremental) Layering:** of new market shaping policies for energy efficient appliances **(Gradual) Conversion**: of appliance manufacturers, after initial resistance, to efficiency agenda. **Reproduction**: of core logic of domestic practices and associated cultural conventions.
2003-2009	**(Radical) Layering**: of new low carbon policies into overarching energy policy alongside cost and security goals. Policies for modular RET niche-regime (onshore wind) switching. **Conversion**: of incumbent-led, large scale centralised business model to RET generation. *New entrant coalition builds pressure for distributed solar generation*	**Reproduction:** Network operators and Ofgem locked in to existing routines and strategies, sweating assets. *Largely unsuccessful attempts to layer low carbon innovation agenda into Ofgem's remit.*	**(Further) Layering**: through stabilisation and extension of efficiency agenda; **Conversion**: of manufacturers and retailers to efficiency agenda **Reproduction**: of core logic of domestic practices and associated cultural conventions. *Advocacy for smart meters to change consumer behaviour*.
2010-2014	**(Continued) Layering / Conversion:** of incumbent model to low carbon agenda through policy momentum. Extending modular substitution to onshore, biomass. *Building public and political opposition to RETs. Increasing public attention to energy costs*.	**Reproduction:** despite attempts to layer climate change into regulator's remit. Architectural stretching (grid expansion) under prevailing socio-institutional arrangements **Displacement**: distributed generation (solar); prosumption *Emergence of visions, experiments and advocacy coalitions for smart, flexible system*.	**Reproduction**: of efficiency agenda through policies and manufacturer/ retailer strategies. Expanding range of appliances and stronger policy for niche substitution in lighting. **Reproduction**: of core logic of domestic practices and associated cultural conventions.
2015-?	**De-Layering / reversal?:** decreasing low carbon policy support for several RETs – new political support for gas, nuclear and offshore wind.	**Gradual or constrained displacement:** emerging real world reshaping of tech. architecture. Socio-institutional changes lagging.	**Uncertain:** post-Brexit, uncertainties may affect efficiency agenda.

whole system architectural reshaping. Recent technological innovations, including smart meters and grids, storage and distributed electricity prosumption are starting to change the operational logic of whole system linkages (in terms of material, energy and information flows). However, despite this technological momentum, socio-institutional changes appear to be lagging behind.

This pattern has been well documented in historical studies of radical innovations (e.g. Nelson, 2002), where the co-evolutionary dynamic between technologies and institutions can involve mismatches. Lagging institutional change can impede the wider implementation of new technologies. For example, the Capacity Market policy instrument was designed, in principle, to stimulate architectural reshaping (as a systemic policy instrument, Wieczorek and Hekkert, 2012), but was constrained in implementation by deeper institutional logics, so instead reproduced the status quo.

A further problem concerns long-term actor and institutional stability in the network subregime (which has barely changed, compared to the generation and consumption subregimes). Arguably, this has become the reverse salient (Hughes, 1983) constraining further whole system reconfiguration. Full realisation of the newly emerging architecture-reshaping technologies discussed above implies a shift for the network subregime from being a buffer to an active integrator of the whole system. But existing actor roles, identities and operational routines remain largely locked in to those established in the 1990s. Whether the necessary changes can be made through policy layering and actor conversion or via more radical displacement in terms of actor configurations and deeper institutional logics is uncertain.

Either way, changes to the network subregime are likely to be the instigator of further architectural reshaping that would reach out and interact with the generation and consumption subregimes, possibly creating a new meta-regime architecture. When, how and at what pace this happens will depend on the interplay and struggles between the creation of new meta-regime institutions and the reproduction of long-standing underpinning institutional logics.

6. Conclusion

This paper aimed to reconnect with the founding assumption of transition studies to study whole system transition, by analyzing techno-economic and socio-institutional developments across the entire chain of production, distribution *and* consumption. In particular, we demonstrated how attention to system architecture provides additional insights for assessing low-carbon progress and more generally for the imagery and pattern of whole system transition.

The approach was demonstrated through an analysis of low carbon changes in the UK electricity system between 1990 and 2016. The focus on whole system architecture provided some novel insights. First, we showed how significant low carbon progress had been achieved on the basis of policies incentivizing low carbon innovations, while the deeper institutional logics, including the architecture of the three subregimes remained relatively stable. This meant incremental and then more radical modular innovations have so far dominated.

Second, however, we showed how more recent technological changes were starting to disrupt the pre-existing architecture, potentially triggering the emergence of a new phase of architectural reshaping. But this new phase may be constrained because socio-institutional changes appear to be lagging, especially in respect of how the network subregime intermediates between generation and consumption. Deeper institutional logics associated with neoliberal policy exert more constraints for architectural reshaping than for earlier modular changes. Furthermore, the UK government's preference for working with incumbents within a stable whole system architecture appears to have been re-asserted through the 2015 energy reset and other recent policies. The lack of change in deeper institutional logics helps to explain the ease with which the government, in 2015, was able to scrap many previous low carbon policies. Recently strengthening commitments to market neoliberalism and withdrawal of state intervention is likely to impede implementation of recently developed smart technologies and opportunities to experiment with new business models, ownership arrangements, organizational configurations and system architectures (e.g. distributed generation).

Third, in contrast to the conventional single point source niche-regime overthrow imagery of system transition, the UK electricity whole system exhibited an imagery of *gradual reconfiguration*, constituted by: 1) multiple sources of change, both incremental and radical; 2) a stepwise interplay between different types of reconfiguration dynamic, modular and architectural, which lead to 3) unevenness in the speed, depth and scope of change across and between components and subregimes.

We finish with some wider reflections about how our focus on whole system architecture and reconfiguration dynamics might contribute to broader debates on sociotechnical system transition. The first reflection relates to how we conceptualised and demarcated a whole system as a unit of analysis for investigation. While our intention was to broaden the unit of analysis for the study of system transition, we acknowledge that our boundary demarcations imply that some relevant developments were not included in our empirical analysis (e.g. commercial or industrial consumption, electric vehicles, electric heating). To address this, future research could usefully study changes in linkages between societal domains (e.g. electricity, mobility and heating), because such changes might become significant in constituting a broader 'great reconfiguration' across multiple whole systems. As a second reflection, we acknowledge that our whole system approach focused more at the level of 'global changes', which meant that our attention to micro-struggles, contestations and more fine-grained learning processes was limited to a small subset of the most significant instances. Misa's trade-off between macro and micro approaches remains a challenge for whole system analysis, but advancing the approach is likely to need both global and local studies. Thirdly, our study showed that architectural reshaping is becoming more significant for low carbon transitions (in electricity systems). This means that future transition studies in could fruitfully focus on system linkages to complement the many studies that have focused on specific instances of single, modular innovations.

In terms of generalizability, we are not suggesting that other whole systems will necessarily follow the same sequence of reconfiguration as we identified for the UK electricity system. In Germany for example, early deployment of renewables was accompanied by significant architectural reshaping, enacted through major changes in socio-institutional arrangement (e.g. decentralised, small-scale wind and solar, enacted by new entrants). Also, other large systems, such as mobility, may exhibit different reconfiguration patterns because they have a different architecture in terms of linkages between subsystems, in particular the ways that the production and consumption systems are aligned and coupled. For example, changes in the automobility regime towards electric powertrains cannot be deployed without immediate and significant changes to driving practices. Or more broadly, modal shifts between transport modes (car to train) or in *how* existing technologies are used (e.g. car sharing) place much more emphasis on changing practices and cultural conventions than on radical (modular) technology change.

So, while we are *not* claiming that the exact pattern of whole system reconfiguration observed in the UK case study is generalizable, we suggest that two outcomes from the current study are. First, we think that the approach of taking whole system architecture seriously, using our identification of several reconfiguration dynamics, can fruitfully be applied to study other whole systems to reveal different reconfiguration patterns. Second, we expect that these differences will show that they do have a 'family resemblance' that differs from the conventional imagery of system transition: system transition need not involve wholesale change to all components and the entire architecture in one fell swoop. In other words, gradualism in process does not necessarily equate with incrementalism in outcome. In contrast to the dominant overthrow model of system transition, we therefore argue that the study of whole system transition should be open to the idea that discontinuous outcomes might come about through gradual reconfigurational processes. This view may be starting to take hold more generally in accounts of social change, because "[t]he history of modern social ideas has misled us into associating piecemeal change with disbelief in institutional reconstruction, and a commitment to such reconstruction with faith in sudden and systematic change" (Unger, 2005: 31–32).

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