Governance of interactions between infrastructure sectors: the making of smart grids in the UK

Abstract

This paper uses historical analysis to explore the evolution of interdependencies between the electricity and information and communication technology (ICT) sectors in the UK. It explores the role of governance in shaping the interface between these two sectors, and subsequent implications for smart grid innovation. The analysis focuses on three periods between 1940 and 2016, with distinct institutional logics: state ownership, privatisation, and transitions to sustainability.

The interactions between the electricity and ICT sectors are analysed through Raven and Verbong's (2007) typology: competition, symbiosis, integration and spill-over, drawing on social-technical transitions theories and discussed in terms of rules and institutions; actors and networks; and technology, artefacts and infrastructures of socio-technical regimes.

The paper finds that a way to encourage more spill-overs and integration between the electricity and the ICT sector is through a more symmetrical and integrated governance approach that takes into account the needs and characteristics of both sectors.

Keywords: smart grids; ICT; electricity; infrastructure interdependencies; governance

1. Introduction

A core aspect of socio-technical transitions towards sustainability is expected to be the adoption of new technologies, processes and behaviours. The development of low(er) carbon infrastructure and the reduction of carbon emissions associated with energy production and use, in particular often call for varying degrees and forms of interactions between technologies, actors and rules between sectors. Smarter electricity systems, including smarter grids, are a case in point, and are often seen as a key component of more sustainable energy systems in the UK and beyond (e.g. National Infrastructure Commission 2017).

This paper explores the development of smarter electricity grids in the UK by exploring interactions between the electricity and information and communication technology (ICT) sectors. It uses transitions theories to carry out a historical analysis of these interactions in three time periods: the period of state-ownership that began after the second world war; the period of privatisation and liberalisation in the 1980s and 1990s; and the period since 2000, in which the sustainability of electricity and other sectors has received more significant attention. It does so primarily using a typology of interactions between different socio-technical regimes developed by Raven and Verbong (2007), with an emphasis on how these interactions have been governed.

The paper includes a particular focus on the period from 2010 to 2016, and the electricity network demonstration projects funded through the Low Carbon Network Fund (LCNF). The paper explores the implications of the historical context for the more recent governance of innovation that cuts across these two infrastructure sectors. It also considers the impacts on the characteristics of, and barriers to, innovation of smart grid development. The paper concludes by exploring the implications for sustainable transitions in the UK. This conclusion also reflects on the lesson learned from applying Raven and Verbong's typology for understanding existing and emerging interdependencies between sectors.

Discussions of smart grid development have been predominantly focused on technical, legal and economic dimensions of change (Xenias et al 2014; Abdulhadi et al 2013; Al-Omar et al 2012; Verbong and Geels 2010; DECC 2009), with limited analysis of governance mechanisms and their implications for the interactions between the electricity and ICT sectors. An original contribution of the paper is the discussion of the interactions between the electricity and ICT sectors in the UK. To our knowledge, historical analysis of these interactions, and the implications for network innovation, has not been carried out in a UK context. Bolton and Foxon (2015) offer an abridged reflection on the first years of the LCNF, while this paper deals with the Fund in more detail and places its governance in a longer term historical context.

Building on work dedicated to transformations at the sectoral level (see Dolata 2009 for discussion of sectoral systems of innovation), Erlinghagen and Markard (2012) examine the main catalysts for transformation within sectors. Specifically, how ICT firms can trigger transformation (development of smart grids) in the electricity system through their capacity to create variety and break up rigidities in existing systems. Therefore, this paper also builds on

Erlinghagen and Markard's (2012) work on the dynamics between incumbents and new entrants in smart grid projects at EU level between 2000 and 2011, while extending the analysis to the UK until 2015. Bolton and Foxon (2015) call for more "innovation friendly" governance of smarter electricity systems, spanning from the early stage development of local networks, through to the transformation of incumbent national grids. Although literature examining the critical nature of interdependencies between infrastructure sectors is rapidly growing, attention to the governance dimension of these interdependencies is still somewhat limited. This paper aims to address this gap.

Section 2 introduced the concepts of smart grid and infrastructure interdependencies. Section 3 provides a literature review of the transitions concepts used in this paper, mainly socio-technical regimes, multi regime interactions and paradigmatic systems. Section 4 covers how governance is interpreted and applied in the analysis. The methodology of the paper is outlined in Section 5. Historic account of sector development and interactions of the electricity and ICT sectors in the UK in the three periods between 1940s and 2016 is presented in Section 6, followed by a discussion of the governance arrangements and interactions between the two sectors in Section 7. Section 8 discusses the implications of historic interactions for innovation towards smart grid development in the UK, while Section 9 concludes on the implications of governance arrangements and interactions for innovation.

2. Infrastructure interdependencies in socio-technical transitions: smart grids

Infrastructure interdependencies capture the way different elements within an infrastructure system or elements from two or more infrastructure systems influence each other. Infrastructure sectors interact with each other all the time and through a variety of interdependencies. For example, Rinaldi et. al. 2001 distinguish between physical, cyber, geographic and logical interdependencies. They can occur either by design, necessity or evolutionary reasons (Carhart and Rosenberg 2014). Interdependencies between infrastructure sectors are responsible for a range of growing risks, uncertainties, and opportunities for policy makers, industry and society (Hiteva and Watson 2016). Complementary or functional relationships between sectors or competing decision−making processes can trigger trade-off effects (Buldyrev et al. 2010). For example, a failure in ICT may threaten both the transport and electricity sectors due to their increasing reliance on 'smart' or 'intelligent' technologies. By contrast, structural similarities and/or a symbiotic relationship between sectors may create opportunities for sectors to benefit from each other (Watson and Rai 2013). The nature and intensity of these interdependencies evolves over time, creating pressure for more coordination of governance arrangements (Carhart and Rosenberg 2014), and could also change with the introduction of new technologies and governance arrangements. However, infrastructure systems can be 'locked in' to silo-based governance arrangements where the regulatory regime for each sector operates independently, and sometimes in competition with each other (Watson and Rai 2013; Hiteva and Watson 2016).

Interest in using infrastructure interdependencies to enable sustainability transitions, through intertwining sustainability practices between different sectors is growing (Tran et al. 2014; Bolton and Foxon 2015; Lockwood 2016). Smart grid developments are the focus of policy and innovation efforts because of the opportunities they offer as part of the transition to more sustainable energy and transport services (National Infrastructure Commission 2017). Definitions of smart grids can vary depending on the level of integration between the electricity and ICT technologies, however the term most commonly denotes "electricity networks that can intelligently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies" (European Technology Platform smartgrids 2010). They usually involve two-way flows of electricity and information based on arrangements of metering systems and sensors. Electricity flows from energy suppliers to customers are measured and controlled in order to optimize and adjust energy production and consumption. To achieve this, smart grids integrate advanced ICTs, automation, sensing and metering technologies, and energy management techniques based on the optimization of energy demand and supply into a traditional power grid (Al-Omar et al 2012). Smart grids could form a tightly integrated ecosystem of operators and users coupled with enabling functions and information exchange infrastructure (Abdulhadi et al. 2013).

However, in practice, advancements in the development of smart grids can be challenging as they often involve the development of new interfaces between sectors and trialling new processes and technologies. Furthermore, smart grid development is an evolving process, taking place within an increasingly complex landscape due to: infrastructure sector liberalisation; a growing range of stakeholder groups involved in negotiating the trade-offs between multiple objectives, such as efficiency and innovation; increasing interdependencies and complementarities (Raven 2007) between infrastructure sectors; and shared objectives of environmental protection (Watson and Rai, 2013). The foundations for these interactions have evolved over a long period of time and play a decisive role in shaping the speed, rate and nature of smart grid innovation and its governance. The electricity sector is already dependent on ICT infrastructure for system (frequency and load) control, in the form of software updates, upgrades, hotlines and remote access support through "electronic highways" (Gottwald 2009). Electricity is required to run all ICT equipment and smart grids will not be able to function without it[1] (Engineering the Future 2011). However, the integration of these two sectors will need to overcome significant barriers if smart grids are to fulfil the promise they hold for the transition towards sustainable energy systems.

3. Cross-sector interactions in socio-technical transitions

A number of conceptual and theoretical frameworks have previously been used to explain socio-technical change within infrastructure sectors, including the Multi-Level Perspective

[1] For example, most mobile and fixed network distribution and exchange points have only one hour battery backup.

(MLP) (Geels 2005, Geels and Schot 2007), Large Technical Systems (LTS) (Hughes 1983, Coutard 1999) and Technological Innovation Systems (TIS) (Markard and Truffer 2008; Carlsson and Stankiewicz 1991). These have been used to explain transformation through different catalysts such as landscape pressures (Geels and Schot 2007), innovation within niches (Geels and Raven 2006) or the transformative capacity of technology (Dolata 2009; Erlinghagen and Markard 2012). As approaches they capture the non-linear and interrelated nature of sectoral transformations, including how changes in one sector may prompt and feed on changes in another sector (Erlinghagen and Markard 2012).

Although infrastructure interdependencies are discussed in this paper in terms of interactions across *sectors*, its approach builds on literature that focuses on interactions across multiple *regimes*. Within this literature, infrastructure sectors are represented as "socio-technical regimes" (Geels 2004; 2006), where technical systems are embedded within the wider societal context and constitute a "seamless web" of interactions between technical and non-technical components (Hughes 1987). A regime encompasses the network of actors and social groups; the formal, cognitive, and normative rules that guide the activity of actors; as well as the material and technical artefacts and infrastructures (Geels 2006).

Regimes interact in multiple ways, and although they are often governed in silos, what occurs within one infrastructure sector or 'regime' can change the scope of that regime, as well as affect other, related regimes. Dolata (2009) explains how technology developed elsewhere can drive the transformation of existing regimes. For Hughes (1987) system builders can also be catalysts for transformation beyond individual sectors. Aminzade (1992) and Hakansson and Waluszewski (2002) see the intersection of two regimes as a source of structural change and variety leading to new combinations of existing resources and innovation (Erlinghagen and Markard 2012). Both Hughes (1987) and Summerton (1994) have focused on processes of change within technical systems, while recent research on systems innovation has emphasizes the co-evolutionary and interdependent nature of processes which affect socio-technical regimes (Geels, 2004).

Multi regime interactions across more than one infrastructure sector have received some limited attention in the literature. Raven (2007) has examined how the waste and electricity regimes in the Netherlands have co-evolved, and how they have become more symbiotic and integrated due to innovation in biomass technology. In another context, Geels (2007) has shown how interactions between two regimes contributed to the rise of a new musical style. This paper uses Raven and Verbong's (2007) typology of interactions that was developed to explain the emergence of combined heat and power. They distinguish four types of interactions between the gas and electricity regimes in the Netherlands:

- *Competitive*: when regimes start fulfilling similar functions. Competition could happen when actors from different regimes compete for the same resources (e.g. raw materials, finance), access to infrastructures, produce products for similar market or compete for institutional arrangements. Competition can lead to substitution (one regime taking over from the other) or increasing variety (multiple regimes providing similar functions).

- *Symbiotic:* when regimes start reaping mutual benefits from each other's existence. In the case of symbiosis between two regimes, regimes can even become mutually dependent. More generally, symbiosis might result in stronger and more stable ties between regimes (e.g. through long-term supply contracts) or generate innovative activities.

- *Integrative*: when previously separated regimes become one. The most obvious way of integration is on the actor level, but most likely this will change organizational routines, ways of producing and using, ways of researching etc. Technology can also be a 'hard' form of integration as is the case of combined heat and power (CHP). So far different types of integration are recognised. Integration could be partial and not lead to the complete disappearance of multi-regime setting. Disintegration refers to a situation when an existing regime splits up.

- *Spill over*: when regimes transfer experience to each other. This includes less explicit forms of spill over, e.g. when actors build upon routines from past activities in a different regime and apply them to their activities within the current regime. Spill overs can also be more explicit, such as when tariff structures for one regimes are copied to another. This type of interaction is often indirect and occurs at the level of cognitive, institutional, normative rules.

Raven and Verbong (2007) find that these types of interaction are not exclusive and can occur simultaneously or sequentially. Changes in one regime may obstruct expected changes in another regime. Similarly, in a case study of the UK water and electricity sectors, Watson and Rai (2013) show how structural similarities and a symbiotic relationship between sectors may also create opportunities that allow sectors to benefit from each other. This has important implications for policies or strategies designed to enable a more integrated approach to infrastructure transitions such as ambitions to develop smarter electricity grids.

Erlinghagen and Markard (2012) examine more closely the private agents involved in interactions between the ICT and electricity sectors in the EU. They consider the transformative capacity of technologies and the strategies and resources of actors who own them (Dolata, 2009). They distinguish three types of actors: incumbents within the focal sector, start-up firms and entrants from another sector (which they term 'adjacents'). Erlinghagen and Markard (2012) analyse the influence of actors from outside a focal sector and their interactions with incumbent actors, to understand the extent to which they drive or accelerate sectoral transformation. Such a focus is particularly relevant if technologies from 'outside' play a key role in the processes of transformation (Dolata 2009). This could lead to formerly unrelated sectors becoming more closely integrated, prompting actors to move across sectoral boundaries to exploit existing technological resources (Nicholls-Nixon and Jasinski 1995). The distinction between adjacent and incumbent sectors is useful in understanding the nature and direction of interactions and innovations between the ICT and electricity sectors.

However, the nature and means of interactions between different infrastructure systems or elements can change from one period to the next. For Kaijser (1999) each historic period is defined by a "paradigmatic system" – an infrastructure system on which other similar systems are modelled. This involves transferring some basic characteristics of an institutional framework developed for one sector to other similar systems. To some extent the institutional frameworks of existing infrastructure systems (i.e. socio-technical systems) are reproduced and adapted when new infrastructure systems are introduced. Kaijser (1999) also argues that infrastructure systems have both a hard, technical side and a soft, institutional side (including the legal and economic frameworks of the system). Therefore, interactions between different regimes can involve both their soft and technical sides.

Transitions from one paradigmatic infrastructure system to another can happen because of dramatic technical changes in the former system and the halt in the expansion of the latter. The emergence of a specific institutional framework of a new infrastructure system can result from: a) the functions and properties of the system; b) the general institutional framework and the current overall political context at the time; and c) the legacy from previous (paradigmatic) systems. The institutional framework of an infrastructure system is not fixed but changes over time, with changes to the three areas outlined above. For example, as systems grow, some components or parts can lag behind. Change can also result from far reaching changes in technology affecting many infrastructure systems simultaneously. For example, the rapid changes in ICT technologies and systems are now having wide-ranging impacts through digitalisation of other sectors, including electricity.

4. Governance

Whilst smart grids involve multiple interactions between the electricity and ICT sectors, they have also been shaped by the governance of these two sectors. Governance "looks at the interplay between state and society and the extent to which collective projects can be achieved through a joint public and private mobilization of resources" (Pierre 2011, p. 5). Governance here is used as a dynamic concept focusing on the processes of steering and coordinating (Pierre and Peters 2000), rather than in terms of institutions and governing structures (Mayntz 2004). Governance captures the idea that government should steer public and private actors into achieving societal goals, by using strategic capacities such as the ability to make policy, as well as softer means, like networks, voluntary agreements, and partnerships (i.e. instruments of New Governance) (Freeman 1999, Salamon 2001). Steering, however, is not limited to government and can involve other public actors, like regulators, as well as users. Whatever the steering mechanisms or other governance instruments used they are not neutral (Peters 2001). They may also have secondary consequences spanning beyond the targets of a given program or policy (Hood 2007).

Governance arrangements and instruments for steering are closely linked to the prevailing socio-technical regime. The key regime actors and different governance styles can be oriented towards the dominant regime logic, which can include hierarchy, market, network, and community (Pierre and Peters 2000). Managerial type governance (emerged from literature on reforms of public administration (Kickert 2007)), focuses on output-oriented steering. Its overarching political values are oriented towards choice, competition and efficiency in public services, with the objective of market creation (Heinelt 2008).

The key mechanisms of governance can vary from sector to sector, as they will respond to key sector characteristics. Tightly coupled infrastructure systems (grid-based systems possessing a system-specific grid of rails, pipes or wires) for example, traditionally require a high degree of coordination. These tend to be led by a single organisation, responsible both for maintaining the grid and for operating the flow through it. Loosely coupled systems, tend to be built and operated by many different organisations (Perrow,1984). The degree of coupling in a system can change over time (Kaijser, 1999, p.6). The nature of steering and coordination in a tightly and loosely coupled systems can significantly vary. Co-ordination is particularly important for electricity, where real time balancing between supply and demand is required. This means that the electricity and gas regulator (Ofgem) and the companies that operate electricity networks have particularly important roles to play in system governance and operation.

5. Methodology

Analysis of changes and challenges within individual sectors is well established in socio-technical transitions literature (Geels and Verhees 2011; Penna and Geels 2015; Geels, 2002, also Raven and Makkard), while there are still challenges in developing methodologies for analysing interdependencies between two or more sectors (Erlinghagen and Markard 2012; Watson and Rai 2013; Raven and Verbong 2007; Raven 2007). This paper analyses the interactions between the electricity and ICT socio-technical regimes using Raven and Verbong's (2007) interactions typology and Erlinghagen and Markard's (2012) distinction between core actors. We recognise that these typologies may not be exhaustive. Interactions will be presented and discussed using a historical analysis that focuses on the main elements of socio-technical regimes set out by Geels (2006): rules and institutions; actors and networks; and technology, artefacts and infrastructures. These elements are used to anchor the discussion of governance, but they are not fully applied. This approach is justified given that the primary focus of the paper is on the interactions between these two sectors and their implications for governance, rather than on the evolution of each sector.

The case study uses a combination of primary and secondary data, to enhance validity and reliability. The primary data used in this study was collected through semi-structured interviews with key stakeholders. These included Low Carbon Network Fund (LCNF) project participants, regulatory experts, ICT and electricity company representatives, government agencies, governance participants and industry associations. The secondary data analysed includes grey literature (policy documents and industry reports) and peer-reviewed academic articles. There is a significant amount of information available on the development of the electricity and telecoms sectors which we have built on. Secondary data was reviewed to provide an overview of the most significant developments within each sector over the past 65 years, to map interactions between them for the same period, and to guide the formulation of interview questions.

The term ICT is used throughout the paper for uniformity. However, it is worth noting that this term is ambiguous. ICT here refers to both the telecommunications and IT sectors (which could be considered as two separate sectors rather than subsectors), and the integration of the two has evolved through the three periods of consideration. This definition of ICT is highly heterogeneous, with some elements of the so-called ICT infrastructure largely independent of each other (e.g. data centres and software service industry). Although telecoms are more asset based than software development, each has played a more prominent role at different periods. As the two have evolved, so have the boundaries between them changed and blurred in some aspects. However, they both play a role in the interactions between the two sectors, and the development of smart grids.

The governance interactions between the electricity and ICT sectors in the UK have taken a variety of forms over the past few decades. Hence the historic analysis is divided into three distinct time periods, each corresponding to specific dominant governance paradigms (Helm 2005): 1) *State ownership* (1940s-1980s) during which utility regimes were characterised by state ownership; 2) *Privatisation* (1980s to 2000) during which most utilities in the UK were privatized and utility sectors were liberalised; and 3) *Transitions to sustainability* (2000-2016). Differences between the start of the periods for the electricity and ICT sectors exist, with some milestone technologies and activities taking place earlier than the 1940s for example. The third period is called 'Transitions to sustainability' in recognition of the increased emphasis on emissions reduction since the publication of the Royal Commission on Environmental Pollution report on energy and climate change in 2000 (RCEP, 2000). The development of the ICT sector during this period has not been driven by sustainability concerns to the same extent. However, technological advances in software development and growing demand for high speed broadband have created opportunities for further application of ICT to help facilitate the transition towards a more sustainable electricity (and energy) sector.

The three periods are discussed in turn in the section below. Each sub-section starts with a more sector specific accounts of key developments (in terms of rules and institutions; actors and networks; and technology and infrastructures, with key points summarised in tables 1, 2 and 3, and continues with an account of the key interactions between the two sectors.

6. Historic account of sector development and interactions of the electricity and ICT sectors in the UK: 1940s-2016

a. State ownership (1940s-1980s)

After the Second World War, the electricity sector was driven by the need to meet the increasing demands of a growing economy (Surrey 1996). Electricity generation, transmission and supply was nationalised, and a significant nuclear investment programme was implemented during the 1970s and 1980s (Pearson and Watson 2011). By the late 1980s, private generation of electricity was almost completely displaced by the public sector (Surrey 1996). The four elements of electricity sector in the UK (generation, transmission, distribution and supply) and their organisations the Central Electricity Generating Board, National Grid, the 12 Regional Area Boards (all covering England and Wales) and vertically integrated companies in Scotland and Northern Ireland were state-owned monopolies. The demand for electricity grew significantly in the first few decades of state ownership driven by economic growth and an expansion in the use of electricity across the economy. This coincided with the introduction of progressively larger power plants and an excess of generation capacity (Sherry 1984).

The nationalisation of the telecoms industry took place in 1912, much earlier than the electricity sector. During this first period telecoms were a 'natural monopoly', with one operator British Telecom (BT) having control over the telecoms network and services (Aharoni 1986). The focus of the sector was on the delivery of standard telephony services (Interview ICT expert 2014). However, while the 1960s and 1970s were characterised by over-investment in power stations for the electricity sector, there was under-investment in telecoms leading to huge waiting lists for new telephone lines as demand increased rapidly. Technology advancements were beginning to reduce the capital investment required for entry into the market and the prospect of greater competition became feasible (Rutter et al. 2012).

Table 1. Key developments within the electricity and ICT/telecoms regimes in the period of state ownership

Regime elements	Electricity	ICT/Telecommunications
Rules and institutions	State owned, driven by security of supply and growing demand; expanding capacity and source of generation	Focus on delivery of standard telephony services
Actors and networks	All state-owned monopolies; Regional Area Boards and vertically integrated companies	BT a 'natural monopoly', with control over telecoms network and services
Technology, artefacts & infrastructures	Larger power plants; introducing nuclear power and excess of generation capacity	Under-investment and growing demand (for new telephone lines) led to lack of capacity; Technology advancements reduced capital investment for entry into the market and increased prospects for greater competition

Interactions between electricity and telecommunications sectors in the UK before utility privatisation took the form of a symbiotic customer-supplier relationship. Electricity was supplied to the telecoms sector, and telecommunication infrastructure enabled the control of electricity networks through centralised dispatch boards, regional and national control centres, where Supervisory Controls and Data Acquisition (SCADA) systems were widely used. Although there were agreements between British Telecom (BT) and local electricity distribution companies since the 1950s for the sharing of poles, relatively little pole-sharing took place. Poles in the UK tended to only have one use, and there was a lack of provision for communications cables on electricity poles (and vice versa) (Rowe 2012). Institutionally, the two sectors functioned as separate socio-technical regimes with limited interaction between actors, institutions and rules governing them. There were similarities, however, between the two sectors: both were publicly owned, operated as 'natural monopolies', and faced growing demand for electricity and telecommunications services (Stern 2014). Since the early 1950s until their privatisation in the 1980s, the electricity and telecom sectors have been undergoing similar structural transitions in terms of their ownership, objectives, management and oversight. It is through the privatisation and liberalisation process that big differences between the two started to emerge.

b. Privatisation (1980-2000)

The UK privatisation programme of the 1980s and 1990s brought significant changes to the ownership, market rules and institutions in a wide range of sectors, including electricity and telecommunications (Rutter et al. 2012). The majority of the electricity sector was privatised in 1988/89. As with other sectors, an independent regulator was established: the Office of Electricity Regulation (Offer). Its main objectives were to reduce costs, to provide incentives for short-term efficiency and to promote competition. In June 1999, Offer was merged with the gas regulator, Ofgas, to form the Office of Gas and Electricity Markets (Ofgem).

In addition to regulating monopoly networks, the regulator also implemented controls on retail prices. These were gradually removed by the end of the period as competition was extended to household consumers. The regulator's role continued to change throughout this period – and subsequently. Whilst Offer's focus was on current consumers, Ofgem's primary duty was widened, to include the interests of both existing and future consumers. This was supplemented by social and environmental guidance that was designed to ensure that government policy objectives were taken into account.

Innovation has not been explicitly included within Ofgem's duties, though it has been part of more recent social and environmental guidance. As this paper will show, Ofgem actively promoted innovation in the third period. During the second period, however, a standard 'RPI-X' formula[2] was used to regulate monopoly network charges, which had a negative effect on innovation and R&D (Bolton and Foxon 2011). Previously high levels of investment under state control allowed companies to 'sweat the assets', and to deliver significant efficiency savings via increasingly stringent price controls (Helm 2009). The companies that inherited network assets therefore lacked an incentive to invest or to innovate.

Table 2. Key developments within the electricity and ICT/telecoms regimes in the period of Privatisation

Regime elements	Electricity	ICT/Telecommunications
	Economic regulator (Offer) and a regulatory (RPI-X) formula introduced;	Economic regulator (Oftel) and a regulatory (RPI-X) formula,

[2] RPI-X is a price cap approach which limits price increases to the rate of inflation (Retail Price Index) minus an efficiency factor (X). Thus, the higher the value of X, the more efficiency gains the DNO has to make before they can see a return. The value of X has been determined by the regulator for every price control period. For more details, see Hall and Foxon (2014).

Rules and institutions	Progressive tightening up of price controls; Attempts to increase competition in generation and retail; Growing importance of environmental regulation; Introduction of an integrated pollution control agency (HMIP) and later on of the Environmental Agency	along with a price cap was introduced; Rapid increase of competition; Regulation closely aligned with national and EU competition policy
Actors and networks	Large private utility companies;	BT and private licence holders
Technology, artefacts & infrastructures	Decreasing investment in electricity networks; Preference for the construction of large gas-fired power plants	The communication and the information technology sectors converged and the ICT sector emerged

The British Telecommunications Act 1981 paved the way for the privatisation of BT and enabled the licencing of other operators to run telecommunication systems. Following the Littlechild Report the telecoms sector was also regulated through the RPI-X formula, and a price cap on retail tariffs (Mirrlees-Black 2004). As noted above, this RPI-X formula was subsequently applied to other sectors, including electricity (a case of regulatory spill-over). This was a period of big financial, technological and regulatory transformation for the sector. In the space of a few years the telecommunications sector transformed from a natural monopoly, to a fast growing and competitive sector, where innovation was increasingly profitable, with short periods of return (Interview ICT expert 2014).

A key similarity of the two sectors was the importance placed on competition and privatisation. In practical terms for telecoms, this involved the creation of a challenger to BT (Mercury was set up in 1982) and a duopoly model introduced in 1983 that limited the number of long-distance fixed link operators to BT and Mercury for seven years. In the electricity sector this involved the creation of competition in generation by breaking up the incumbents and progressively opening up the retail market by ending franchises of regional electricity companies.

The differences between the electricity and ICT sectors had significant impacts on the development of both sectors. While in the case of the electricity sector it reduced the impetus for infrastructure investment and introduced stringent economic regulation. In the case of the ICT sector it created an impetus for innovation and infrastructure investment, opening up the UK to international investment. As a result the ICT sector was driven by market forces to a larger extent, offering more opportunities for entry to the market and for quicker financial profit (Interview ICT expert 2014).

Over this period electricity transmission, distribution and supply companies started using communications technologies more than before in operating and controlling their networks, strengthening the symbiotic interactions between the two sectors. Partial integration between the two was facilitated by the sharing of infrastructures likes poles and transmission and to a lesser extent transmission lines. Since the 1980s fibre-optic communications cables were laid over some of the bigger transmission lines to provide connections between major sub-stations and control centres. SkyWrap is a process that has been used since 1982 to install fibre-optic cables onto power transmission lines by wrapping it securely onto one of the power conductors. Since then several other technologies have become available to add fibre-optic cables to transmission and distribution power lines: ADSS, OPPC and AccessWrap. The different technologies vary in the extent to which they require cooperation between electricity and telecoms companies in their maintenance. The integration was partial because although there was partial integration at the technology level, on the actor level, DNOs and BT continued to have separate ways of organising and using the infrastructure. For example, all overhead electricity distribution poles in the UK are owned by DNOs and they are responsible for maintaining them. British Telecom also own poles. Most DNOs have fibre installed for their own SCADA and protection circuits but this tends to be limited to HV pylons (Rowe, 2012).

Energis Communications Limited (Energis), was set up in 1992 as Telecom Electric as a result of a demerger from the UK's National Grid Company to provide telephony services, e-mail and internet access, using an optical fibre network, partially deployed via the overhead power transmission network of the grid. Energis provided a number of services based around its core platforms of ISP, Transmission, IP Networking, Contact Centre Solutions and Voice (traditional switched telephony) (Rowe 2012). It introduced the latest at the time technology - synchronous digital hierarchy (SDH) to the telecoms network (Warner 1997), thus directly competing with BT in the provision of voice services and increasing the variety of services provided within the telecoms sector.

c. Transitions to sustainability (2000-2016)

This period was characterised by significant policy and technological change. Environmental concerns, particularly with respect to climate change, gained prominence in the electricity sector at EU and national level. This was joined by renewed concerns about energy security in the mid-2000s. Overall renewable electricity capacity increased dramatically between 2000 and 2014 from 3GW to 24.2GW respectively (DECC 2015), through the introduction of several support mechanisms like Renewables Obligation (RO); and targets to source 10% of UK electricity from renewables by 2010 and 15% of UK overall energy from renewables by 2020 (Pearson and Watson 2011), and the introduction of a Feed-in-Tariff (FIT) scheme for small-scale renewable installations (of less than 5MW) such as solar photovoltaics (PV) (DECC 2012). Energy efficiency policy was also given more emphasis, for example through the introduction of successive obligations on energy suppliers.

Table 3. Key developments within the electricity and ICT/telecoms regimes in the period of Transitions to sustainability

Regime elements	Electricity	ICT/Telecommunications
Rules and institutions	Increased prominence of climate change and energy security concerns; Long-term targets for the reduction of GHGs introduced;	New ICT economic regulator (Ofcom) with more hand-off approach; Introduction of Digital Economy policy

	Active economic regulator	
Actors and networks	Ofgem's remit widened to include the interests of future and current consumers; A joint energy and climate change department (DECC) was established; Ofgem introduced two regulatory "add-ons": IFI and RPZ;	Opportunities for new small and large companies to enter the market; Venture capitalists started investing in ICT companies; Establishment of digital catapult centres nationwide;
Technology, artefacts & infrastructures	Increased RES installations and capacity	Introduction of mobiles and internet; Mass rollout of broadband; 3G and 4G introduced

The ICT sector has also undergone dramatic changes as a consequence of market reforms and technological progress (Corrocher 2003; Erlinghagen and Markard 2012). Following liberalization value chains were re-organised, business models changed dramatically and many new actors entered the market (Li and Whalley 2002; Hacklin et al. 2009). In contrast to the electricity regulator, the ICT regulator Ofcom (which replaced Oftel in 2002) had a more hands-off approach in attempt to enable more competition in the market (OECD 2002; Interview ICT expert, 2015). The mass rollout of broadband, as per EU and national policy, in turn enabled higher rates of innovation and ICT companies became attuned to new business opportunities outside of the ICT sector (Nicholls-Nixon and Jasinski 1995), like smart grids (Erlinghagen and Markard 2012; Interview ICT expert, 2015).

The expansion of internet products and services also had a huge impact on the ICT sector globally and in the UK, transforming the way ICT companies operate and finance innovation. Venture capital became used to financing ICT innovation because of the quick returns of investments (Interview ICT expert 2014), while the UK government began investing in the digital economy, with the introduction of the Digital Economy Act 2010 and the establishment of multiple catapult centres nationwide since 2013. However, the internet is still not defined as a utility service, severely limiting opportunities for the regulation of ICT sector**.**

Interactions between the two sectors increased significantly during this period. Integration became much more important, prompted by high-level policy goals such as climate change mitigation and advances in ICTs. ICTs began to be discussed as an important component of more sustainable electricity systems, particularly smarter electricity networks that balance supply and demand more actively, including the integration of smarter meters and electric vehicles. Electricity infrastructure became more dependent on ICTs, particularly within generation and transmission, but also in metering and billing. ICTs were also seen as increasingly important for integrating renewable energy generation sources into the grid and for balancing international energy flows (Wissner 2011). Developments in integrated electronic circuits, control systems, and ICTs significantly improved the functionality of advanced metering and demand response technologies (Siano 2014). During this period the electricity sector started digitising traditionally isolated energy network control systems and connecting previously isolated operational networks and IT systems (New Power 2014).

Key components of smart grids that advanced in technological terms during this period include smart meters. The UK government is implementing a national programme to replace all electricity and gas meters (in domestic and non-domestic sites) with smart meters. The aim is to complete this by 2020, though the pace of installation has been slow. There are now over 11 million smart and advanced meters operating across homes and businesses in the UK (BEIS, 2018). Such meters can enable more accurate billing, real-time feedback to consumers as well as electricity contracts that include time-of-day pricing. They could also enable remote control of consumer appliances to allow the cost-effective scheduling of non-time-critical loads (Siano 2014).

This period is also characterised by a number of institutional changes to increase collaboration between actors involved in smarter grid developments. The Smart Grid Forum (SGF) was created by the government and Ofgem in 2011 to focus on the development of smart grids, and to build on the work of another public-private body, the Electricity Network Strategy Group (ENSG) in 2009. The Forum aimed to address commercial and technical changes and the barriers the network companies faced in implementing smart grids in the UK, and to improve co-ordination between the firms and government agencies involved (Connor at el. 2014). Although the Forum brought together a broader range of stakeholders, its membership is oriented towards the electricity sector, and includes lower representation from the ICT sector, and thus can be considered a limited form of soft integration between the two sectors.

Whilst Ofcom has not been formally involved in these groups, it has started to analyse the implications of the greater integration of ICTs into other sectors through emerging technologies such as the 'Internet of Things' (IoT) (Ofcom 2015). The IoT can enable previously unconnected devices to communicate and share data and as such can be considered as a form of hard integration between the two sectors. By the end of 2016 there were more than 13million devices connected via the IoT within the UK and are said to increase to over 150 million by 2024 with the progress of smart meters roll out (Ofcom, 2017).

This greater emphasis on smarter electricity systems has also included significant new incentives for technology demonstration and deployment. Most notably, Ofgem introduced specific incentives for network innovation and smart grid demonstration projects, starting with the 4th Distribution Price Control Review (DPCR4) that ran from 2005-2010. Prior to this, distribution network operators had almost stopped conducting their own R&D and had reduced their innovation capacity steadily since privatisation (Lockwood 2015).

As part of DPCR4, Ofgem introduced two regulatory "add-ons" to build innovation capacity in DNOs: the Innovation Funding Incentive (IFI) and Registered Power Zones (RPZ) in 2005. RPZs encouraged the development of bounded networks, through offering additional revenue to DNOs, whilst IFI projects aimed to enhance the technical development and management of distribution networks. In 2006, the IFI was extended to the end of DPCR5 (2010-15). The introduction of RPZ and IFI was considered to be an important first step by Ofgem in introducing greater levels of distributed generation, intermittent generation, smart meters, other smart energy technology and demand response, which are constitutive aspects of smart grids (Hall and Foxon 2014). IFI rapidly increased the levels of innovation spending by DNOs over a relatively short period of time (Interview Electricity Network Innovation expert 2014; Interview ICT expert 2014).

A much more ambitious smarter grid demonstration programme – the Low Carbon Networks Fund (LCNF) - was introduced in 2010. This Fund allowed DNOs to spend up to £500m of consumers' money over the five-year period of DPCR5. Its main aim was to help DNOs become more commercially and technically innovative (Interview Regulatory expert 1, 2014). So far, the LCNF has supported two tiers of projects: smaller projects in Tier 1 and larger 'flagship' projects in Tier 2. Tier 1 (a total of 41) projects are for a maximum of three years and cover trialling new equipment, arrangement, application or operational practice with direct impact on the distribution system. Tier 2 (a total of 23) projects have a more stringent and complex selection procedure, and cover automated network management, flexible connection contracts, demand side response and commercial arrangements.

This process was followed by changes to regulatory incentives that moved away from efficiency incentives and towards more long-term, output-oriented innovation (Müller 2011). Ofgem replaced the RPI-X system with a system known as RIIO (which stands for Revenue = Incentives + Innovation + Outputs). A key feature of RIIO is to promote more efficient capital expenditure by extending the regulatory period from 5 to 8 years, and to directly reward companies that "successfully implement new commercial and charging arrangements" through a range of new measures like the Network Innovation Competition, the Network Innovation Allowance and the Innovation Roll-Out Mechanism. This has also introduced the potential of a new array of actors and mandates for existing ones, such as aggregators, that could emerge with a more distributed electricity system (for more details see Bell and Gill, 2018).

7. Governance arrangements and interactions

In line with the dominant regime logic during the first period the key regime actors were state-centric and network and utility incumbents exercised monopoly over the mobilisation of existing infrastructure and resources. Symbiotic interactions between the two sectors were mostly the result of operating decisions aimed to facilitate coverage of the services and were focused on technologies and access.

In the second period symbiotic interactions were driven by expansion of operational and market capacities. The second period saw the introduction of a number of new entrants, private (mostly large international companies) or companies which have emerged from privatised monopolies, such as BT. In this sense, regime incumbents still retained significant power both in the electricity and telecoms markets and in terms of regulation. Competition between the two regimes was limited to the provisions of voice and data services (between BT and Energis) and contributed to the increased variety of available services and technologies. However, BT's strong monopoly position meant that Energis could not overtake or substitute it in the telecoms sector.

As shown in Table 4, during this period interactions between the two sectors developed further, involving regulatory and market frameworks for operation. Interactions during the periods of privatisation and transitions to sustainability included spill-overs – the transfer of knowledge and routines – mainly from the ICT to the electricity sector in the context of smart grids technologies and services. In line with the dominant regime logic (Pierre and Peters 2000), economic regulation and market mechanisms were instrumental for steering the two sectors and the interactions between them, opening up opportunities for competition between the two sectors. Steering was output-oriented and governance was coordinated through overarching political values of choice, competition and efficiency in public services, with the objective of market creation (Heinelt 2008). During this period, monopoly infrastructures, such as electricity and telephone cables, were opened up to some extent through unbundling and liberalisation, creating more opportunities for interaction between the two sectors. Growing UK and EU environmental regulation, introduced a new institutional layer in the second period which in turn introduced changes to the electricity sector and created more opportunities for interaction between the two. This trend continued into the third period and was mobilised by concerns about climate change and the need to reduce carbon emissions.

Although the RPI-X formula was initially developed and tried in the telecoms sector, during the second period, and applied in the electricity sector, this was not due to what Kaijser calls the (1999) paradigmatic nature of the former. In fact, this was one of many 'transfers' of basic institutional characteristics between multiple sectors which took place during the second period. Although, both sectors shared the same formula, there were significant differences in the way in which it was applied. In the electricity sector the formula covered transmission and distribution, while in the ICT sector it was applied to mobile activities, with the exclusion of internet services. This in turn led to significant difference between the two sectors, with implications for innovation.

Table 4. Summary of interactions between the electricity and ICT sectors from 1950s until 2015

Types of interactions	**State Ownership**	**Privatisation**	**Transitions to sustainability**
Competitive	_	Energis and BT in voice and digital service provision	Energis and BT in voice and digital service provision
Symbiotic	Electricity for telecoms; telecoms for electricity	Intensified symbiotic activities	Mutual dependency
Integrative	Marginal. Contractual arrangements for pole sharing between DNOs and BT	Some technological integration	Further technological integration and co-ordination of actors, driven by smarter grids
Spill-over	_	From telecoms to electricity: economic regulation (RPI-X formula)	From ICT to electricity: technology and software

Throughout the three periods of analysis there is a consistent symbiotic relationship between electricity and ICT, which strengthened the ties between the two regimes, especially in terms of technology, resulting in a specific strand of innovation activities dedicated to the development of smart grids. It can also be argued that the prolonged symbiosis between the two regimes has resulted in their mutual dependency. While in the first and second periods the two sectors are co-existing, in the third period they start to integrate.

In the third period we see a recognition at national and firm level, of the existing symbiotic interactions between the two and increase of governance actions to build on them. Economic regulation continued as a primary steering mechanism of governance within and between the two sectors. A wider variety and size of firms entered both markets and the state took an active role in steering infrastructure policy towards closer interactions between the two sectors. However, the governance of the two sectors still remained largely siloed due to the distinct logics of the two economic regulators: Ofgem and Ofcom. While the economic regulatory for electricity (Ofgem) exercised extensive oversight of many elements of the electricity regime, the ICT sector was predominantly steered through market mechanisms, with Ofcom played a more limited role. The government also had a large influence over the direction of both sectors – for example through the introduction of Electricity Market Reform in 2013. These differences in governance structures within the two sectors ultimately played a big role in shaping the opportunities and the nature of their interactions.

Strategic capacities of the state to make policy also played a big role in this period through the introduction of digital economy and climate change policy, and an array of supporting mechanisms for their development, such as digital and urban catapult centres. This period also saw the development of new ‘softer’ instruments of New Governance for interactions between the two sectors through networks like the SGF and the ENSG, and partnerships, like those developed within the LCNF.

In the third period, while technological integration between the two sectors strengthens, a distinct characteristic is the development of institutional frameworks (agencies, working groups and networks) designed to facilitate governance interactions between the two sectors. Examples include the Smart Grid Forum, the UK Regulators Network (UKRN) and the Electricity Networks Strategy Group. This points to a progression of developing multi-dimensional (technological, market and institutional) interactions between electricity and ICT, and a slow process of adaptation. If this trend continues, the development of smart grids in the UK could be a story of gradual change rather than radical innovation and realising the potential of smart grids depends on the extent to which the pace of change can be increased to enable further spill overs and integration, both at technological and institutional level.

Overall, the final period provides a much richer range of interactions, and integration on the actors and network level through smart grid groups and in terms of technologies such as smart meters and IoT. Most literature on smart grids places the electricity sector at the centre of analysis. For example, Erlinghagen and Markard (2012) refer to the electricity sector as the focal sector, established electricity distribution companies as incumbents, and ICT companies which offer smart grid solutions as adjacent. However, some argue that the ICT layer of smart grids constitutes as much as 70% of the smart grid infrastructure due to the need for computing platforms, operational systems, business applications and business services (Lima 2011; Interview ICT expert 3). This was also reflected in the make-up of most smart grid innovation 'Tier 2' projects funded by the LCNF (Interview ICT experts 1 and 2, 2014). Similarly, the institutional actors and networks mobilised for the development of smart grid innovations in the UK, such as the DNOs and the SGF were anchored in the electricity sector and were closely linked to electricity incumbents (such as the National Grid).

The historical analysis shows that integration between the two sectors is relatively recent and so far involves a handful of technologies and processes. These include specific pilot and demonstration projects through schemes such as the LCNF and the smart meter roll out, both of which have been anchored in the electricity sector. This, along with the different roles played by economic regulation in both sectors, has been reflected in technological interactions between the two. In technical terms, the integration of ICT infrastructure into power systems has mostly been carried out using a layering approach. This involves adding the ICT infrastructure once the electrical infrastructure is already built, with the two infrastructures planned almost independently (Hadjsaid et al. 2011).

8. Implications for innovation towards smart grid development in the UK

Building on the historical analysis of governance arrangements and interactions between the electricity and ICT sectors, we identify two important relationships that have shaped the development of smart grids in the UK so far: economic regulation and innovation; and the relationship between incumbents and new entrant firms.

a. *Economic regulation and innovation*

The discussion so far made clear the central role of the electricity sector in the development of smart grids in the UK and the importance of economic regulation and the RPI-X formula as key steering mechanisms. During the first 20 years after privatisation, there was a primary focus in the application of this formula on short term cost reduction and operational efficiency. Until recently, the income of DNOs has been linked to the expenditure they are allowed by the regulator to invest in their networks, set every five years in a distribution price control review (DPCR). This led to diminished incentives for innovation and investment in R&D programmes in the sector (Jones and Yarrow 2010; Lockwood 2016). The regulatory framework was designed to 'sweat the assets' and reduce day-to-day operational costs (OPEX), providing network companies with a skewed incentive to solve network performance or constraint problems through reinforcing their networks and expanding their asset base (Bolton and Foxon, 2015).

As Peters (2001) argues, steering mechanisms or other governance instruments are not neutral, and may have secondary consequences spanning beyond the targets of a given program or policy (Hood 2007). This is evident in the case of steering through economic regulation for the electricity sector, which led to a sharp reduction in R&D by the DNOs. Some industry representatives argue that the economic regulation fostered an environment that was not tolerant towards experimentation and failure, and one which favours established technologies, and small incremental change in network systems. They note that it also made DNOs less capable of innovating. Although DNOs have established innovation teams and future technology groups as a result of more recent regulatory incentives, they are relatively small and linked to specific projects (Interview Electricity Network Innovation expert 2014; Interview ICT expert 2014).

This, in turn, has led to limited use of and investment in more active network management (ANM) and smart grid development so far (Interview Electricity Network Innovation expert 2014; Interview ICT expert 2014). The regulation of DNO activities has been identified as a significant barrier to the development of ANM (Bolton and Foxon 2015). The positive views about the impact of the LCNF is that it has provided a significant reputational incentive for DNOs to be involved (Interview Regulatory expert 2014; Interview DNO representative 2014) and to make changes to their business operations. Ofgem sees the strongest evidence for that change in the fast track submissions for the DNOs business plans for the next Price Control Period (DPCR6), as all DNOs have submitted actual savings to the cost of network reinforcement from trials on automated network management and demand side response (Interview Regulatory expert 2014).

A recent review of the LCNF by Bell et al (2016) provides further detailed context for these views. The review shows that there has been mixed success in the adoption of new innovations trialled through LCNF in 'business as usual' practice by DNOs. Nevertheless, it concludes that 'much useful knowledge has been generated by the projects supported by the LCNF'; and that 'compared with the situation before IFI and LCNF, the DNOs are considerably more active in R, &D and open to innovation' (Bell et al, 2016: xviii).

b. Incumbents and new entrants

The unintended consequences of economic regulation which have led to a disconnect between the characteristics of smart grid innovation (i.e. ICT led) and the opportunities for its application (i.e. in the electricity sector) are closely linked to the role of incumbents and new entrants in smart grid development. As a tightly coupled infrastructure system, electricity is in need of a high degree of coordination. In the second and third periods coordination within the sector and with the ICT sector has been dominated by economic regulators and incumbent firms such as DNOs and the 'Big Six' vertically integrated utilities, despite some erosion of their market share in the past four years (Lockwood and Eyre 2016). Incumbents are expected to drive innovation within the framework of economic regulation.

In contrast, the ICT sector can be thought of as a loosely coupled system built and operated by many different organisations, with the economic regulator Ofcom, just one of many actors, whose mandate is limited to certain segments of the sector. Despite BT's dominance in areas linked to existing broadband and telephone connections, new entrants are expected to drive innovation within markets. The existing community of start-ups in electricity network innovation is relatively small, particularly in the application of ICTs to networks. Access to the DNOs for small and medium ICT companies is difficult and joining innovation projects such as LCNF is one of the few opportunities for these companies to work with DNOs. A key barrier to participation involves the softer New Governance mechanisms of developing electricity focused networks and partnerships, and well as informal and formal everyday rules and terms of operation. At the time of data collection, all but one DNO, were using GE's software tools for network management. As one interviewee from the ICT sector stated, DNO procurement officers tend to take the view that "*The answer is GE. What is the question?*" (Interview ICT expert 2014). These practices are in line with Erlinghagen and Markard's (2012) claim that incumbent ICT firms dominate smart grid innovation.

9. Conclusion: interactions, governance and innovation

Overall, the interactions between the two sectors have been predominantly symbiotic but competing priorities between them and differences in regulation have resulted in significant transaction costs of working together. Although there has been more coordination between regimes through the establishment of joint organisations like the government-industry SGF, DNOs have had more influence than ICT companies within these organisations. Cross-cutting institutions have not overcome the fundamental barriers to integration.

This has led to some integration between the two sectors, where innovative technology from the 'outside', adjacent ICT sector can lead to transformation of the incumbent electricity sector (Dolata 2009). A closer integration, would see actors moving across sectoral boundaries to exploit existing technological resources (Nicholls-Nixon and Jasinski 1995) to create new services and process, leading to sectoral transformation (Erlinghagen and Markard 2012). However, what we see in the third period is the establishment of the electricity sector as a focal sector for smart grid development, without the transfer of basic institutional characteristics from it to the adjacent ICT sector and vice versa, thus falling short of becoming a paradigmatic system as understood by Kaijser (1999). The application of ICT innovations to the incumbent electricity sector have been limited by the dominant electricity sector governance arrangements of steering and coordination. The nature of the LCNF and the layered technical integrations between the two sectors do not challenge the existing dominant mechanisms of governance, of steering through economic regulation, or reconciling the big differences between them. In this sense we can argue that the soft, institutional side of the incumbent sector is shaping the opportunities for interactions with the adjacent ICT sector. This suggest that with the current governance arrangements, despite ambitions for smart grid development driven by climate change concerns, the electricity and ICT sectors could continue to develop in largely siloed trajectories.

Apart from the application of the RPI-X formula in electricity network regulation in the second period, spill-overs have tended to come from the ICT sector to the electricity sector through the use of ICT platforms, processes and technology by DNOs. This is because DNOs have received most of the government funding for smart grid innovation and are best represented in relevant governance structures. It is likely that this will continue to have an effect on the innovation capabilities of the UK in developing smart grids, the speed with which such capabilities can be developed as well as the type of smart grid projects that emerge.

The analysis of the interactions between the two sectors shows that multi-regime dynamics can both create barriers as well as opportunities for innovation, in line with Raven and Verbong's (2007) findings. Raven and Verbong' (2007) typology is useful as a starting point in investigating the multiform interactions between the two sectors. However, the discussion of dominant governance mechanisms characteristic of specific regimes and periods in time, allowed us to better understand the barriers and drivers of cross-sector interactions. In the third period we see that governance arrangements in the incumbent sector (electricity) act as barriers to innovation and can limit the scope and speed of spill over from the ICT to the electricity sector. The power dynamics between incumbent and adjacent sectors, as presented by Erlinghagen and Markard (2012) and the discussion of paradigmatic systems by Kaijser (1999) helped us understand why despite growing technical transfers (i.e. ICT innovations into the electricity sector) and cross-sector institutions smart grid development in the UK isn't more advanced.

These findings highlight the value of historical analysis to inform the development of further policy and regulatory reforms seeking to improve cross-sectoral integration. For the case of smarter electricity grids, they emphasise the importance of understanding the socio-technical elements (rules and institutions, actors and networks, and technology) within different sectors, the interactions between them, and how they can act as enablers of (or barriers to) change. A way to encourage more spill-overs and integration between the electricity and the ICT sector is through a more symmetrical and integrated governance approach that is takes into account the needs and characteristics of both sectors.

Acknowledgement:

The authors would like to thank all the reviewers for their suggestions towards improving this manuscript. The research reported in this paper was part of the UK Infrastructure Transitions Research Consortium (ITRC) funded by the Engineering and Physical Sciences Research Council under Programme Grant EP/I01344X/1.

References

Abdulhadi I., McArthur, S. and Burt, G. 2013, Lessons Learned from Deployed Smart Grid Protection and Control Strategies, HubNet Position Paper Series.

Aharoni, Y. 1986, The Evolution and Management of State-Owned Enterprises, Cambridge: MA: Ballinger Publishing, p.264.

Al-Omar, B., Al-Ali, A. R., Ahmed, R., and Landolsi, T. 2012, Role of Information and Communication Technologies in the Smart Grid, Journal of Emerging Trends in Computing and Information Sciences, Vol. 3, No. 5, pp.707-716.

Aminzade, R. 1992, Historical Sociology and Time. *Sociological Methods & Research*, *20*(4), 456–480.

Buldyrev, S.V., Parshani, R., Paul, G., Stanley, H.E., Havlin, S. 2010, Catastrophic cascade, Letter, Nature, Vol. 464, pages 1025–1028.

Department for Business, Energy and Industrial Strategy (BEIS) 2018, Smart Meters. Quarterly Report to end March 2018. 2018. Great Britain. Experimental National Statistics, accessed at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/712151/2018_Q1_Smart_Meters_Report_.pdf

Bell, K. and Simon, G. 2018 Delivering a highly distributed electricity system: technical, regulatory and policy challenges. Energy Policy, 113. pp. 765-777. ISSN 0301-4215.

Bell, K, Frame, D and McArthur, S. 2016, A Review and Synthesis of the Outcomes from Low Carbon Networks Fund Projects. Final Report. London: UK Energy Research Centre and HubNet.

Bolton, R. and Foxon, T. 2011, Governing infrastructure networks for a low carbon economy: Co−evolution of technologies and institutions in UK electricity distribution networks. Competition And Regulation in Network Industries, 12(1), pp. 2−26.

Bolton, R. and Foxon, T. 2015, Infrastructure Transition as a socio-technical process – implications for the governance of energy distribution networks in the UK, Technological Forecasting & Social Change, 90, 538-550.

Carhart, N. and Rosenberg, G. 2014, Towards a Common Language of Infrastructure Interdependency, Infrastructure Interdependence, Presented at the International Symposium for Next Generation Infrastructure, IIASA Vienna, October 2014.

Carlsson. B. and Stankiewicz, R. 1991, On the Nature, Function and Composition of Technological Systems, Journal of Evolutionary Economics, Vol. 1, Issue 2, 93-118

Committee on Climate Change (CCC) (2017) Energy prices and bills: impacts of meeting carbon budgets. London: CCC.

Connor, P., Baker, P., Xenias, D., Balta-Ozkan, N., Axon, C. and Cipcigan, L. 2014, Policy and regulation for smart grids in the United Kingdom, *Renewable and Sustainable Energy Reviews*, 40, pp.269-286.

Coutard, O. (ed) 1999, Governing large technical systems. London: Routledge.

Darby, S.J., Liddell, C., Hills, D. and Drabble, D. 2015, Smart Metering Early Learning Project: synthesis report. Department of Energy and Climate Change, London.

Darby, S. 2014, Smart energy technologies in everyday life. Smart Utopia? *Energy Research and Social Science*, 1: 240-241.

Department of Energy and Climate Change (DECC), 2014, *Smart Metering Implementation Programme. Third annual report on the roll-out of Smart Meters*.

Department of Energy and Climate Change (DECC), 2009, *Smart Grids: The Opportunity*.

Department of Energy and Climate Change (DECC), 2015, *UK Energy Statistics, 2014 & Q4 2014*.

Dolata, U. 2009, Technological innovations and sectoral change Transformative capacity, adaptability, patterns of change: An analytical framework, Research Policy, Research Policy 38 (2009) 1066–1076.

Engineering the Future, 2011, Infrastructure, Engineering and Climate Change Adaptation – ensuring services in an uncertain future, accessed at http://www.raeng.org.uk/publications/reports/engineering-the-future

Erlinghagen, S. and Markard, J. 2012, Smart grids and the transformation of the electricity sector: ICT firms as potential catalysts for sectoral change, Energy Policy, 51, 895-906.

European technology platform smartgrids, 2010, *Strategic deployment document for Europe's electricity networks of the future*, Brussels.

Geels, F.W. 2007. Feelings of discontent and the promise of middle range theory for STS: examples from technology dynamics. Science, Technology & Human Values 32, 627–651.

Geels, F.W. 2004. From sectoral systems of innovation to socio-technical systems Insights about dynamics and change from sociology and institutional theory, *Research Policy* 33, pp. 897–920.

Geels, F. 2006. Major system change through stepwise reconfiguration: a multi-level analysis of the transformation of American factory production (1850-1930), *Technology in Society* 28, pp.445-476.

Geels, F.W. 2005. Processes and patterns in transitions and system innovations: refining the co-evolutionary multi-level perspective. Technological Forecasting & Social Change 72, 681–696.

Geels, F.W. 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Research Policy 31, 1257–1274.

Geels, F.W. & Penna, C.C.R., 2015. Societal problems and industry reorientation: Elaborating the Dialectic Issue LifeCycle (DILC) model and a case study of car safety in the USA (1900-1995), Research Policy, 44(1), pp. 67-82.

Geels, F.W. and Raven, R. 2006, Non-linearity and Expectations in Niche-Development Trajectories: Ups and Downs in Dutch Biogas Development (1973–2003), Technology Analysis & Strategic Management, Vol. 18, Nos. 3/4, 375–392

Geels, F.W. Schot, J.W., 2007. Typology of sociotechnical transition pathways. Research Policy 36, 399–417.

Geels, F.W. and Verhees, B., 2011. Cultural legitimacy and framing struggles in innovation journeys: a cultural-performative perspective and a case study of Dutch nuclear energy (1945–1986). Technological Forecasting and Social Change 78.

Gottwald, S., 2009, Final Report On Study on Critical Dependencies of Energy, Finance and Transport Infrastructures on ICT Infrastructure, On behalf of the European Commission DG Justice, Freedom and Security, available at: https://ec.europa.eu/home-affairs/sites/homeaffairs/files/e-library/docs/pdf/2009_dependencies_en.pdf

Gray, D. 2014, Coherence and stability in regulatory policy, In: Presentation at RPI Conference, Ofgem, London.

Hacklin, F., Marxt, C., & Fahrni, F. 2009. Coevolutionary cycles of convergence: An extrapolation from the ICT industry. Technological Forecasting and Social Change, 76(6), 723–736.

Hadjsaid et al. 2011 should be: Hadjsaid, N., and Sabonnadiere, J-C., 2013, Electrical Distribution Networks, Whiley Online Library https://onlinelibrary.wiley.com/doi/book/10.1002/9781118601280

Hakansson, H. and Waluszewski, A. (2002), Path dependence: restricting or facilitating technical development?, Journal of Business Research 55, 561– 570.

Hall, S. and Foxon, T. 2014, Values in the Smart Grid: The co-evolving political economy of smart distribution, *Energy Policy*, 74, pp. 600-609.

Helm, D. 2009, Infrastructure investment, the cost of capital, and regulation: an assessment, Oxford Review of Economic Policy 25 (3), pp. 307–326.

Helm, D. and Tindall, T. 2009, The evolution of infrastructure and utility ownership and its implications, Oxford Review of Economic Policy, 25(3), pp. 411–434.

Hiteva, R. and J. Watson, 2016, “Governance of Interdependent Infrastructure Provision”, in The future of national infrastructure: A system-of-systems approach, Cambridge Press, pp.294-309.

Hood, C. 2007, ‘Intellectual Obsolescence and Intellectual Makeovers: Reflections on The Tools of Government After Two Decades’, *Governance* (20)1: 127–44.

Hughes, T.P., 1987, The Evolution of Large Technical Systems in W.E. Bijker, T.P. Hughes, T. Pinch (eds.), The social construction of technological systems. New directions in the sociology and history of technology, MIT Press, Cambridge, MA (1987), pp. 51–82

International Energy Agency (IEA), 2011, Technology Roadmap. Smart Grids.

Jones, S. and Yarrow, G. 2010, Innovation and regulation in energy supply, Economic Affairs 30(2), pp.2-5.

Kaijser, A. 1999, “The Helping hand: In Search of a Swedish Institutional Regime for Infrastructural Systems”, in Lena Andersson-Skog and Olle Krantz, eds., *Institutions in the Transport and Communicatons Industries. State and Private Actors in the Making of Institutional Patterns, 1850-1990,* Science History Publications, Canton, Mass., pp. 223-244.

Konrad, K, Truffer, B. and Voß, J.P. 2008, Multi- regime dynamics in the analysis of sectoral transformation potentials: evidence from German utility sectors, Journal of cleaner production, 16, pp.1190−1202.

Li, F. and Whalley, J. 2002. Deconstruction of telecommunications industry: From value chain to value networks. Telecommunications Policy, 26(9-10), 451-472.

Lima, C. 2011, "An Architecture for the Smart Grid,” IEEE P2030 Smart Grid Communications Architecture SG1 ETSI Workshop. France: IEEE Standard Association, April, pp. 1-27.

Lockwood M (2016). Creating protective space for innovation in electricity distribution networks in Great Britain: the politics of institutional change. *Environmental Innovation and Societal Transitions*, *18*, 111-127.

Lockwood M and Eyre N (2016) The governance of retail energy market services in the UK: A framework for the future. Working Paper. London: UK Energy Research Centre.

Markard, J., Truffer, B., 2008. Technological innovation systems and the multi-level perspective: Towards an integrated framework. Research Policy 37, 596–615.

Mitchell, C. and Connor, P. 2004, Renewable energy policy in the UK 1990- 2003, Energy Policy, 32 (17), pp.1935−1947.

National Infrastructure Commission (2016) Smart Power. London: NIC.

New Power, 2014, Is the UK's energy industry waking up to the threats to cybersecurity?, CYBERSECURITY, Issue 70 / December.

Nicholls-Nixon, C.l. and Jasinski, D. 1995, The Blurring of Industry Boundaries: An Explanatory Model Applied to Telecommunications. Industrial and Corporate Change 4(4):755-68.

Ofcom, 2017, Connected nations report: Data Analysis, *Chapter 6. Internet of Things,* https://www.ofcom.org.uk/__data/assets/pdf_file/0020/108515/connected-nations-internet-things-2017.pdf

Pearson, P. and Watson, J. 2011, UK Energy Policy 1980−2010: A history and lessons to be learned. A review commissioned to mark the 30th anniversary of the Parliamentary Group for Energy Studies. London, Parliamentary Group for Energy Studies.

Perrow, C. 1984. Normal Accidents: Living with High Risk Technologies. New York: Basic Books.

Peters, B.G. 2001, The future of governing. University Press of Kansas, Lawrence.

Pierre, J. & Peters, B. G. 2000. Governance, Politics and the State. Basingstoke: Palgrave.

Pollitt, M. 2010, UK Renewable Energy Policy since Privatisation, EPRG Working Paper 1002.

Pollitt, M. and Domah, P. 2001, The Restructuring and Privatisation of Electricity Distribution and Supply Businesses in England and Wales: A Social Cost–Benefit Analysis, Fiscal Studies, 22 (1), pp.107 : 146.

Raven, R. 2007, Co−evolution of waste and electricity regimes, Multi- regime dynamics in the Netherlands (1969−2003), Energy Policy, 35, pp. 2197 : 2208.

Raven, R. and G. Verbong, 2007, Multi-regime interactions in the Dutch energy sector: The case of combined heat and power technologies in the Netherlands 1970–2000, *Technology Analysis & Strategic Management*, 19 (4), pp. 491:507.

Rinaldi, S.M., Peerenboom, J.P. and Kelly, T.K. 2001, Identifying, understanding, and analysing critical infrastructure interdependencies, IEEE Control Systems Magazine, (21), pp: 11-25.

Royal Commission on Environmental Pollution (RCEP). 2000, *Energy: The Changing Climate*. London: RCEP.

Rowe, J. 2012,Using overhead distribution lines to carry fibre optic cables, Beyond Broadband, http://www.beyondbroadband.coop/kb/using-overhead-distribution-lines-carry-fibre-optic-cables

Rutter, J., Marshall, E. and Sims, S. 2012, THE “S” FACTORS. Lessons from IFG’s policy success reunions, Institute for Government, accessed at: http://www.instituteforgovernment.org.uk/our-work/better-policy-making/policy-successes

Sherry, A. 1984, The power game – the development of conventional power stations 1948-1983, Proceedings of the Institute of Mechanical Engineers.

Siano, P. 2014, Demand response and smart grids—A survey**,** *Renewable and Sustainable Energy Reviews*, Vol. 30, pp.461-478.

Stern. J. 2014, The British utility regulation model: Its recent history and future prospects, Utilities Policy, 31, 162-172.

Summerton, J. (ed) 1994, Introductory Essay: The Systems Approach to Technical Change. Changing Large Technical Systems.

Surrey, J.1996, The British Electricity Experiment, Privatisation: The Record, The Issues,The Lessons, London: Earthscan.

Tran, M., Hall, J., Hickford, A., Nicholls, R., Alderson, D., Barr, S., Baruah, P., Beavan, R., Birkin, M., Blainey, S., Byers, E., Chaudry, M., Curtis, T., Ebrahimy, R., Eyre, N., Hiteva, R., Jenkins, N., Jones, C., Kilsby, C., Leathard, A., Manning, L., Otto, A., Oughton, E., Powrie, W., Preston, J., Qadrdan, M., Thoung, C., Tyler, P., Watson, J., Watson, G. and Zuo, C. 2014. National Infrastructure assessment: Analysis of options for infrastructure provision in Great Britain, Interim results, Environmental Change Institute, University of Oxford.

Verbong, G.P.J. and Geels, F.W. 2010. "Exploring sustainability transitions in the electricity sector with socio-technical pathways." *Technological Forecasting and Social Change* 77 (8) : 1214-1221

Watson, J. and Rai, N. 2013, Governance interdependencies between the UK water and electricity sectors, Working Paper, *ITRC/University of Sussex*.

Warner, J. 1997, Why didn't British Telecom do an Energis?, The Independent, Business, 08 November, http://www.independent.co.uk/news/business/why-didnt-british-telecom-do-an-energis-1292838.html

Wissner. M. 2011, The smart grid: A saucerful of secrets? Applied Energy, 88, pp.2509-2518.

Xenias, D., Axon, C., Balta-Ozkan, N., Cipcigan, L., Connor, P., Davidson, R., Spence, A., Taylor, G. and Whitmarsh, L. 2014, Scenarios for the Development of Smart Grids in the UK: Literature Review, Working Paper, UKERC.