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Infrastructure transformation as a socio-technical process – Implications for the governance of energy distribution networks in the UK



Ronan Bolton ^{a,*}, Timothy J. Foxon ^b

^a Science Technology and Innovation Studies, School of Social and Political Science, Old Surgeons' Hall, High School Yards, Edinburgh EH1 1LZ, UK

^b Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS29 9HH, UK

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ABSTRACT

This paper seeks to uncover and examine the complex set of governance challenges associated with transforming energy distribution networks, which play a key enabling role in a low carbon energy transition. We argue that, although the importance of such infrastructure networks to sustainability and low carbon transitions in the energy, water and mobility sectors is clear, there is relatively little understanding of the social and institutional dimension of these systems and appropriate governance strategies for their transformation. This may be because the prevalent model of infrastructure governance in the energy and other sectors has prioritised short term time horizons and static efficiencies. In this paper we draw on the social shaping of technology literature to develop a broader understanding of infrastructure change as a dynamic socio-technical process. The empirical focus of the paper is on the development of more flexible and sustainable energy distribution systems as key enablers for the UK's low carbon transition. Focusing on electricity and heat networks we identify a range of governance challenges along different phases of the 'infrastructure lifecycle', and we draw lessons for the development of governance frameworks for the transformation of energy infrastructure more generally.

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1. Introduction

It is widely recognised that the energy systems of industrialised countries are unsustainable and require fundamental restructuring. The growing scientific consensus surrounding anthropogenic climate change along with concerns over energy security and fossil fuel depletion have prompted much discussion over the need to accelerate transformational change towards low carbon energy systems [31,32]. So far, in analyses of energy transitions, much of the discussion has centred around supply side issues with the relative merits of different generation options being debated, along with the various institutional barriers to the diffusion of renewable technologies

e.g. wind power, biomass and solar [30,64,92]. More recently a smaller number of studies have begun to explore the role of the demand side in the energy transition and implications for the way we use energy in our everyday lives [43,65]. However, there have been surprisingly few studies which explicitly explore the network components of energy systems – the pipes and wires – which have unique technical and institutional characteristics [9,33,56,58].

Similar sentiments have been expressed in a recent special section of this journal on "Infrastructures and Transitions" [57], where the authors argued that across a number of sectors (water, energy, transport) the role of infrastructure networks in enabling or constraining broader sustainability transitions will be crucial. They highlighted the importance of infrastructures, whether they are distributive (energy, water), communicative (mobility) or accumulative (waste management), in acting as platforms which enable more

* Corresponding author at: Science Technology and Innovation Studies, Old Surgeons' Hall, High School Yards, Edinburgh EH1 1LZ, UK. Tel.: +44 131 650 6366.

E-mail address: Ronan.Bolton@ed.ac.uk (R. Bolton).

sustainable production and consumption practices to evolve [33]. The authors argued however that the stability of infrastructure systems may ‘pose a major barrier to achieve desired sustainability transitions’ and hence argue the need for a better understanding of the interactions between social and technological drivers for change and stability ([57]: p. 1195).

In this paper we adopt a socio-technical systems approach to analyse the role of energy distribution grids in enabling the low carbon transition in the UK, focusing on the particular governance challenges faced in the electricity and heat sectors. These sectors account for a substantial proportion of UK total energy consumption (approximately 22% and 41% respectively [15]), and along with transport, decarbonising electricity and heat will be key to achieving the UK government’s target of at least an 80% reduction in greenhouse gas emissions from 1990 levels by 2050. In a number of respects (renewables integration, system efficiency, demand side management), distribution grids which can integrate new forms of supply and demand side practices in these sectors will be important enablers for a low carbon transition.

Whilst there has been a degree of focus on the technical and engineering challenges of developing more flexible energy distribution networks, particularly in the electricity sector [22,85], the aim of this paper is to focus on the institutional and governance challenges of transforming energy distribution systems. The paper argues that societies need to move beyond the traditional governance model for distribution (and other energy) networks which prioritises short term efficiencies in incumbent sectors (gas and electricity). A more “innovation friendly” governance model is needed to take into account the challenges to be faced at different stages of what we refer to as the infrastructure lifecycle – from early stage development of local networks, through to the transformation of incumbent national grids. We base our argument on insights from literature on the social shaping of technology and socio-technical systems studies and illustrate it using empirical examples of the UK electricity and heat sectors.

The paper is structured as follows: we begin in the next section by providing a brief literature overview and how we seek to analyse the transformation of distribution grids in the UK. Then, in [Section 3](#), we outline the UK’s prospective low carbon transition, highlighting electricity and heat distribution systems and their importance as enablers for this. In [Section 4](#) we focus on the specific challenges being faced in the electricity and heat sectors in the UK: the electricity distribution case illustrates the difficulties faced in transforming highly regulated incumbent systems which are locked-in to an established technological trajectory, whilst the heat case illustrates the challenges of developing new infrastructures in more local/urban contexts. In each of the cases, we discuss the roles of a range of actors in the transformation process including government, private network operators, local authorities and the energy regulator. In the final sections we discuss the broader relevance of our analysis for low carbon infrastructure transformation more generally, focusing on lessons and insights for the development of more effective and coherent approaches to infrastructure governance.

2. Framing and understanding governance challenges for infrastructure transformation

2.1. A socio-technical understanding of infrastructure change

Realising the benefits of more flexible and sustainable systems of energy distribution will require an understanding of the nature of the governance challenge in transforming large scale and complex infrastructure systems. In order to do this we draw from and operationalise the socio-technical approach to analysing the dynamics and long term evolution of large scale technical systems such as energy infrastructure. This approach is situated within the wider field of the social shaping of technology, a basic premise being that the transformation of technologies and technical systems is not determined by any scientific, technological or economic rationality, rather there are a wide range of social, political and institutional factors which interact in a systemic fashion to influence their development [48,75,80,95]. The approach seeks to understand and unpack coevolutionary interactions between a broad range of social and institutional factors such as politics, culture, institutional frameworks and the strategies and practices of a range of actors including, for example, utility companies, sector regulators, policy makers, and end users [7,27,37].

In the specific case of infrastructure based sectors such as energy distribution, but also including transport and water, we must also consider a number of specific techno-economic characteristics [26,55] which mean that these sectors in particular ‘typically evolve gradually and with only incremental changes along established paths (path-dependency)’, and as a result governing structural changes in these sectors will be ‘even more challenging than in conventional sectors’ [58: p. 115]:

- Infrastructure services are often essential to everyday life and are therefore classed as public utilities or social goods. Systems such as transport, energy and communications produce positive (e.g. economic growth) and negative (e.g. visual and noise pollution) effects which make it difficult to disaggregate costs and benefits into a clear pricing regime.
- Due to the physical and economic characteristics of infrastructure networks, they tend to be natural monopolies, therefore the services they provide are not traded in markets but are subject to some form of influence by the state e.g. through regulation or public ownership.
- Infrastructure networks are large scale and complex technical systems and their successful operation requires the mutual interaction between large numbers of individual components. In order to achieve this technical complementarity, institutional arrangements which coordinate a range of both public and private actors are required [55].

In the sub-sections below, we provide a brief overview of relevant strands of the socio-technical systems literature, and following this we attempt to operationalise key insights to identify and analyse governance challenge in the transformation of energy distribution networks.

2.1.1. Large technical systems

The origins of the socio-technical systems approach can be traced to the early 1980s when a body of literature developed which sought to understand the emergence and long term

evolution of infrastructures, termed Large Technical Systems (LTS) [13,47,88]. Particularly influential has been Thomas Hughes' account of the development of electricity systems in the 19th and early 20th centuries [47]. Hughes' approach was unique in that rather than treating LTSs as purely technical artefacts, he outlined how politics, geography, and influential individuals (system builders) played a role in shaping the early emergence of these systems. Hughes summarises the systems approach as follows:

“Large scale technology, such as electric light and power systems, incorporate not only technical and physical things such as generators, transformers and high-voltage transmission lines, but also utility companies, electrical manufacturers and reinforcing institutions such as regulatory agencies and laws”.

[[47: p. 2]]

A central focus of the LTS literature has been to analyse the ways in which technical systems interact or coevolve with their environment to produce context specific 'technical styles'. In his cross country/city comparison of London, Berlin and Chicago, Hughes [47] showed how cultural, political and social differences between countries were reflected in the technologies that were adopted. In line with the social shaping of technology research agenda [4,5,75], Hughes noted that:

“The style of each system was found to be based on entrepreneurial drive and decisions, economic principles, legislative constraints or supports, institutional structures, historical contingencies, and geographical factors, both human and natural”.

[[47, p. 462]]

In their early stages, electricity systems emerged in specific local contexts, however, over time, as technical or social constraints to system evolution and growth were overcome (Hughes termed these Reverse Salients), the systems developed an inner momentum and became a more coherent set of technologies and institutions. As the process unfolded across cities, regions and eventually nations, system builders were replaced by managers and financiers, with specific forms of technical knowledge becoming codified and institutionalised.

2.1.2. Socio-technical transitions

Whilst Hughes' work accounts for the early emergence and expansion of systems, in more recent years there has been a growing interest in understanding the mechanisms by which established systems undergo structural transformations, or system innovations [38]. The socio-technical transitions approach argues that many contemporary infrastructure based sectors such as water, energy and mobility are experiencing lock-in to unsustainable trajectories resulting from path dependent change and the presence of selection environment which promotes incremental rather than radical innovation [7,91]. Within the literature, the predominant approach to framing and understanding the transformation of such large scale and institutionally embedded systems has been to adopt a multi-level perspective (MLP), where system innovations occur due to interactions between the landscape (macro), regime (meso) and niche (micro) levels [38]. Incumbent systems, or

socio-technical regimes, are relatively stable configurations of institutions, practices and technologies which underpin the delivery of essential societal services e.g. energy supply, mobility, and housing. Over time, the social and technical dimensions of regimes tend to coevolve in a path dependent manner thus making them prone to inertia or lock-in – similar to the momentum concept in the LTS literature. Niches, on the other hand, are less constrained spaces which allow greater scope for agency and for radical technical and organisational innovations to emerge. Activities within regimes and niches are contextualised by broader socio-technical landscapes, which refer to macro-level structural trends in society beyond the influence of individual regimes e.g. climate change, political and economic paradigms. In cases where transitions occur, dynamics within and between the three levels create windows of opportunity for radical innovations, which had been developing in dispersed niches, to diffuse. Depending on the disruptive nature of the innovations and adaptive capacity of the regime [82], this can undermine regime structures, leading to the development of a new type of system.

Developed by a group of Dutch researchers, the approach builds upon a number of historical studies of past transitions where it is observed that structural changes in sectors, or periods of systemic innovation, tend to stretch out over long periods of time – in the region of 50 years – and are characterised by different patterns of transformation called transition pathways [31,40]. Examples of their studies include the transition from sailing ships to steam ships [39], and the development of urban water infrastructures in the Netherlands [37].

2.2. Operationalising insights – an integrative lifecycle approach

In order to operationalise these basic insights of socio-technical systems literatures outlined above to identify and assess key governance challenges associated with the transformation distribution and other infrastructure networks, we propose an infrastructure lifecycle model (Fig. 1). Here, drawing from the LTS insights of Hughes [47] and Kaijser [52] who stress the phased nature of infrastructure evolution, we distinguish between four different stages of the infrastructure lifecycle. Essentially we argue that different types of governance challenges will be faced along the different phases of the infrastructure lifecycle, and these will require policy makers and regulators to move beyond their traditional focus on short term efficiencies. The phases we identify are discussed below.

In the *system building and establishment* phase, new systems emerge within niches e.g. the development of small scale urban electricity systems in the late 19th century. These systems will tend to be geographically dispersed niches with a diverse range of technologies and engineering practices, or technical styles, being adopted in different contexts. In the *system expansion and momentum* phase, as standards develop and dominant designs emerge [54], systems expand and develop an internal momentum of their own [47]. Over time these systems interconnect over wider geographic areas – across cities, regions, nations and even international boundaries. Long term investments are made in fixed assets and this sunken capital reinforces a lock-in to a particular technological trajectory, thus systems become prone to *stagnation and inertia*. Key mechanisms of this lock-in include embedded organisational practices or routines of

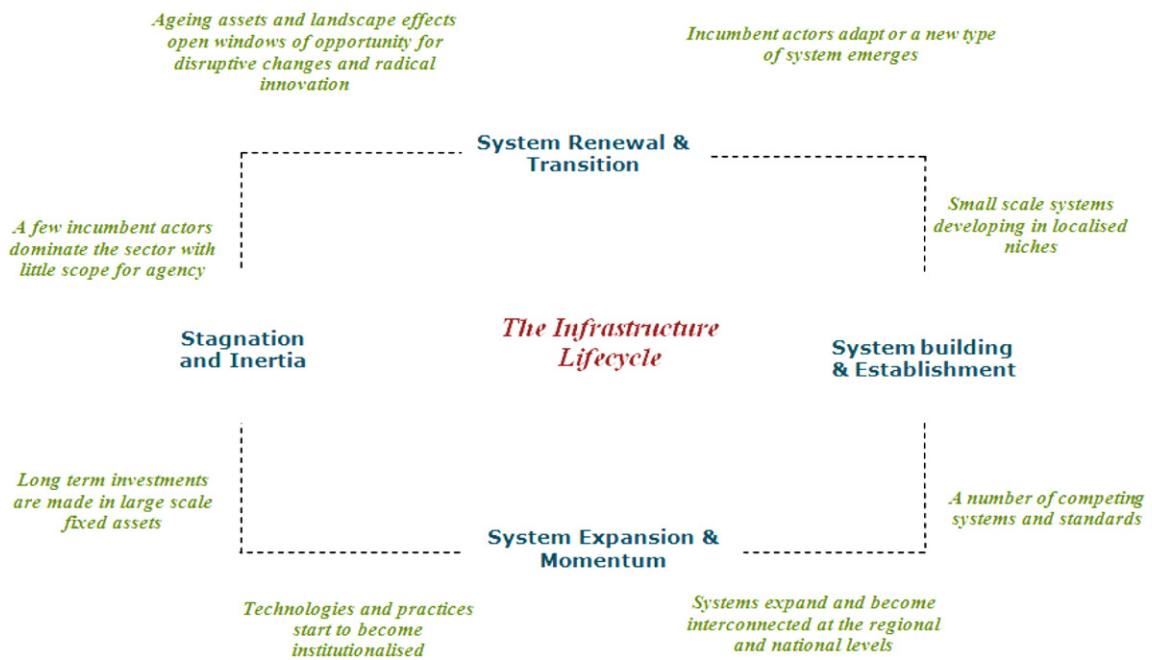


Fig. 1. The infrastructure lifecycle model.

incumbent organisations, benefits of scale economies and network effects, where interconnection of multiple components of a system provides durability. However, over time assets inevitably age, and developments at the landscape level such as climate change and energy security concerns will exert influence, tending to destabilise the regime structures in the *system transition and renewal phase*. The incumbent regime actors either adapt to new circumstances and a system renewal occurs, or a more radical transition process occurs where niche level actors exploit these windows of opportunity, leading to the development of a qualitatively new type of system.

Such a cyclical model of innovation, where long periods of gradual/incremental change are punctuated by short periods of more radical fundamental change, is of course well established in the Schumpeterian inspired literatures on evolutionary economics [24,34,35], industry dynamics [1,54], and more recently the socio-technical transitions approach outlined above [39]. Also, the wider literature on science and technology studies emphasises the complex, non-deterministic and non-linear relationship between technology and society as a distinct problem for policy, and highlights the need to better understand 'the processes of technological change' and 'engage with the content of technological artefacts and practices' [94: p. 5].

The aim of this paper is operationalise these more nuanced understandings of the process of technical change as a socio-technical and cyclical process to address policy and governance challenges related to the role of energy distribution networks in enabling a low carbon energy transition.

3. Energy distribution networks and the UK low carbon transition

In 2008, the UK enshrined into law a commitment to reduce its greenhouse gas emissions by 80% by 2050, and to put in

place intermediate 5-yearly carbon budgets towards this target. Significant contributions to these reductions are expected to come from the electricity and heating sectors, implying potentially radical changes to end-use demands, supply options, and transmission and distribution networks.

In relation to energy distribution in the UK the key phases of the infrastructure lifecycle are likely to be *stagnation and inertia* moving into *renewal and transition* and *system building and establishment* moving into *expansion and momentum*. Our empirical cases of UK electricity and heat distribution networks respectively highlight the nature of the governance challenge being faced at these two different phases in the overall context of the decarbonisation of the UK economy. Before outlining these cases in more depth, in the paragraphs below we briefly discuss the broader relationship between UK energy infrastructures and their role in enabling long term decarbonisation.

Due to the more advanced development of lower carbon options in the electricity sector (e.g. renewables and nuclear) and concerns over energy security due to ageing plant [12,19,74], power sector decarbonisation is generally seen as a short/medium term priority in UK energy policy. Whilst much of the mainstream debate has on the need to deploy new forms of large scale generation (e.g. offshore wind, carbon capture and storage, nuclear) which is connected to high voltage national transmission grids, a number of recent studies have argued that there is also a need to consider new forms of distribution system planning at the local and regional scales. For example, McDonald [59], in reviewing developments in electricity network technologies and concepts, highlighted the importance of active and intelligent electricity distribution networks to maintain power quality with increasing levels of smaller scale intermittent renewable connected to the distribution grids. He argued that 'conventional network design has led to less sophisticated system control and management structures with lower levels

of automation in place' and 'similar to conventional transmission networks, more active network strategies and technologies will be required at the distribution level' (p. 4347).

Heat, unlike electricity, is generally not a grid based system in the UK, rather heating for the majority of buildings is predominantly gas fuelled [3],¹ with 18–20 million individual gas boilers installed in dwellings [18]. Approximately 70% of all domestic, commercial and industrial heat demands in the UK is met from natural gas, largely due to historical reasons, such as the (until recent) availability of relatively cheap gas from North Sea reserves and the development of an extensive gas distribution network since the 1960s/70s [2]. In its recently published heat strategy [21], the UK Department for Energy and Climate Change (DECC) emphasised the need for a diversity of solutions in order to move away from a heavy reliance on gas and decarbonise this sector: this includes the roll out of electric air and ground source heat pumps which extract and recirculate low temperature heat, increased use of biomass boilers and the development of local district heating networks which are supplied from efficient gas-fired or biomass combined heat and power plants. The latter of these proposed solutions will necessitate the development of an extensive network of distribution pipes, particularly in densely populated urban areas. However, as we discuss later in the paper, heat distribution has to date been an underdeveloped aspect of the UK energy infrastructure, unlike more well developed heat markets such as in the Nordic countries.

3.1. Distribution networks as enablers for decarbonisation

The future of energy distribution in the context of the 2050 low carbon transition is of course highly uncertain and likely to be shaped by a range of innovations in other areas of the energy chain (generation, transmission, end use), along with changes to the wider regulatory and policy frameworks governing this energy system [29]. With this in mind, in the subsections below we identify three broad areas where distribution systems are likely to act as important enablers for a low carbon transition across alternative low carbon pathways.

3.1.1. Integration of renewables

Although the overall levels of renewables in the electricity and heat sectors are relatively low, they have been growing in the UK [20],² and therefore the ability of distribution systems to integrate renewables will be crucially important. For example, the connection of microgeneration such as solar PV could result in capacity constraints on the low voltage electricity distribution networks, particularly in densely populated urban areas, whilst rural networks may experience voltage rise issues due to the connection of wind. The ability of distribution network operators (DNOs) to manage more complex flows on their networks will be key. For the case of renewable heat, although it is envisioned that much of heat supply will be electrified [11], the economic prospects of low carbon technologies such as CHP with biomass fuel will be improved by the development of

local heat distribution networks where the heat can be captured. This will be dependent on the nature and density of demand/loads within specific localities [16,76,90].

3.1.2. Promoting energy efficiency

There are a number of ways that sustainable distribution systems could promote energy efficiency, particularly relating to the avoidance of thermal losses. For example, in city scale district energy (DE) schemes involving combined heat and power with district heating (CHP/DH), energy efficiency approaches 70%, as opposed to 40% for conventional plant [53] where the waste heat is 'dumped'. Further savings can be achieved by balancing and sequencing a range of loads, leading to the more efficient utilisation of fuel, compared to a large number of less efficient individual boilers which often operate at part load [77]. Figures from the Department of Energy and Climate Change (DECC) show that if gas-fired CHP were the main energy source for domestic and commercial heat and power, this would save approximately 9.8 MtCO₂ per annum, and if a biomass source is used this could potentially rise to 19.3 MtCO₂ [16]. For the case of electricity distribution, utilising flexible approaches, such as demand shifting [81] and more sophisticated monitoring techniques e.g. thermal ratings, can help to reduce losses, which account for up to 5–6% of electricity distributed.

3.1.3. Promoting DSM

A third area where distribution systems will be important for the low carbon transition is in integrating with the demand side and promoting demand side management (DSM). In the electricity sector, the traditional role of a distribution network has been to reliably deliver power to the customer in a one way direction. However, as we move away from this 'predict and provide' paradigm, the demand side, along with increased storage capacity and interconnection [89], will become a more active component in the electricity system in order to deal with the issue of intermittency. Studies have shown that integrating the demand side with the operation of the upstream asset base can lead to cost savings by reducing capacity margins, offsetting network reinforcements to accommodate low carbon technologies and avoiding investment in expensive peaking plant to deal with intermittency [84]. The UK government is planning to roll out smart metres to all domestic customers beginning in 2015, and because customers are connected to the distribution networks, these systems will become an increasingly important part of developing a more interactive relationship between customers and the electricity system. Such issues have become central to debates surrounding smart grids [17,25].

Of course the changes required to develop a supporting energy infrastructure to realise the low carbon transition go deeper than the technical issues which were emphasised here. In the next section we focus on ways of framing and understanding the governance challenges likely to be encountered in transforming large scale systems such as distribution networks as we enter into the *renewal and transition* (electricity case) and *system building and establishment* moving into *expansion and momentum* (heat case) phases.

¹ Approximately 81% gas, and around 8% electricity and oil.

² Measured against targets set in the EU 2009 EU Renewable Energy Directive, as of 2012 10.8% of electricity generation was from renewable sources, rising from 5.4% in 2008, while the level of heat (and cooling) from renewable sources was 3.2% rising from 2.1% in 2008 (see Table 6.7).

4. Challenges at different stages of the infrastructure lifecycle

Drawing on empirical case studies of electricity distribution and district heat networks we now discuss how some key governance challenges are being encountered in the UK context and discuss the extent to which they are being addressed.

For each of the cases, selected policy documents were reviewed to provide an overview and also to give an outline of the most significant developments which have taken place within each sector over approximately the past ten years. In order to complement this documentary analysis, over forty semi-structured interviews were conducted with key stakeholders throughout the study period (2009–2011). Table 1 below illustrates the range of stakeholders interviewed as part of both cases and the number of interviews conducted in each category. The sections below provide a summary of key governance challenges to be addressed in each case (for a more detailed analysis of the cases see: [6])

4.1. Case #1: from stagnation to transition – developing active electricity distribution networks

The current structure of the electricity distribution sector in the UK emerged following the 1989 Electricity Act which established licences for 14 private regional electricity companies (RECs). Following the Utilities Act in 2000 and the introduction of retail competition, a specialised distribution licence was created for the 14 areas. Over the years, there have been a number of mergers and acquisitions, and today there are seven companies who operate the 14 distribution licences – these are termed Distribution Network Operators (DNOs). Due to the fact that distribution networks are organised as regional monopolies, the distribution of electricity is treated largely as a non-competitive activity which is governed by a sector regulator – Ofgem.

4.1.1. System renewal and transition: the need for active distribution systems

Traditionally, electricity distribution systems have been operated in a passive manner with electricity flowing one way along the value chain from generation, transmission, distribution and on to the end customer [83]. A largely passive distribution and demand side has evolved, with the vast majority of generation being connected at the transmission side and network capacity being sized to meet peak demands.

However, as discussed in the previous section, there are two developments which have called this approach into question and are highlighting the need for renewal and transition: an increasing trend towards investment in small and medium scale generation which is connected at the distribution side, such as solar power and CHP – incentivised by subsidies provided by ROCs and FITs – and the planned roll out of smart metering to all domestic households, due to commence in 2015.

The development of more ‘active’ and ‘smarter’ approaches to network planning and operation is seen as a key strategy to integrate medium and small scale distributed generation and DSM whilst avoiding a large scale and expensive programme of reinforcements [83,86]. Active Network Management (ANM) is an all-encompassing concept involving actively managing both generation and the demand side i.e. ‘controlling the inputs onto the network from generators or storage owners (supply-side options) or the offtakes from the network by customers (demand-side options)’ [36]. However, the regulatory framework governing the activities of the DNOs in the UK has been identified as a significant barrier to the development of ANM [62,96]. Following the privatisation of the UK electricity industry in 1990, the natural monopoly components of the value chain – transmission and distribution – have been subject to periodic price control reviews and the application of incentive regulation. This has had the effect of incentivizing the DNOs to achieve significant cost savings, primarily through reducing the day-to-day costs of running their operations [49], but it has acted as a disincentive to investment in innovative approaches to network management, as DNOs benefit more from reinforcing their networks, thus expanding their asset base [7,61,96].

4.1.2. From static to dynamic efficiencies

In recent years, there has been a growing recognition that the regulatory framework governing distribution networks will need to change in order to promote system renewal and transition and the development of ANM and smarter grids [71]. As discussed above, during the system stagnation and inertia phase, the regulatory framework was designed to ‘sweat the assets’ and reduce the day-to-day costs of operating distribution systems – the operational expenditure or OPEX [7,46]. However, the context has changed due to the ageing of the underlying asset base (much of which was installed during the period of system expansion under public ownership), and the recent shift in focus of UK energy policy towards decarbonisation and transformation, rather than purely cost reduction. This has led to a mismatch between

Table 1
List of stakeholders interviewed.

Stakeholder	Electricity distribution case	City scale DE case
Distribution network operator	7	–
Local authority	–	10
Academia	3	2
‘Big six’ energy supplier	3	–
Specialist DE company/division	–	2
Engineering consultancy	6	1
Electrical engineering manufacturer	1	–
Energy regulator	1	–
Government department	1	1
Government agency	–	1
Industry body	–	2
Transmission network operator	2	–

the regulatory regime designed for the stagnation and inertia phase and the need for distribution networks to enter into the renewal and transition phase. As a result of the growing need for investment in the infrastructure asset base and for companies to develop longer term decision making horizons, the need to align the governance framework with the new phase of the infrastructure lifecycle has become apparent. This has introduced new complexities and risks for the regulator.

Since privatisation, the sector regulator Ofgem has had a clear mandate to reduce the costs of energy distribution and has successfully done so through successive price control reviews by incentivising the network companies to reduce the costs of operating their networks against the RPI inflation index – termed RPI-x regulation [49]. However, issues associated with the need for renewal and system transition, such as increasing numbers of DG connections and the demand for new investment in the capital base (capital expenditure or CAPEX), have raised concerns over a drop in the standards of service quality delivered by the network companies e.g. the number of outages and interruptions to supply. Pointing to a potentially damaging trade-off between the drive for OPEX built into the regulatory framework and the increasing need for efficient CAPEX, Giannakis et al. argue that the strong downward pressure on OPEX ‘may provide firms with distorted incentives that lead them to adopt an inefficient output mix’ because companies have been able to benefit to a greater degree from OPEX rather than CAPEX efficiencies [41]. Also, under the current incentive structure, the strong emphasis on OPEX efficiency may result in a situation where a network operator invests in like for like asset replacements and off the shelf technologies, which have low maintenance costs, rather than innovative ANM based solutions. This drive for short term cost and operational efficiencies since liberalisation has been partially responsible for a drop-off in basic R&D funding across the wider energy sector [50,51]. Ofgem has noted that this lack of emphasis on achieving an efficient system renewal and transition provides network companies ‘with a skewed incentive to solve network performance or constraint problems through further investment in transformers and cables, rather than maintaining existing assets to prolong their life or seeking to reduce or manage load, even when the latter solution is cheaper’ [68: p. 27].

Recognising that the conventional RPI-x approach may not be fit for purpose in the renewal and transition phase, in 2009 Ofgem initiated a review of their approach to regulating energy networks, termed RPI-x@20 [69]. The significant output of the review has been proposals for an adapted regulatory framework which will form the basis of the price control review for electricity distribution in 2015 [73], known as ‘Revenue = Incentives + Innovation + Outputs’, or RIIO. This has as its central feature to accelerate the move towards an outputs-led regime where, in order to mitigate against the risks of poor service quality outlined above, the regulator specifies certain performance criteria, with higher returns for those companies who deliver these at a lower cost. This form of ex-post evaluation marks a significant change from the conventional approach where companies were given a greater degree of autonomy in how they achieve efficiencies during a price control period. As part of this, RIIO will see the introduction of differential treatment of network companies, i.e. ‘Network companies could earn a below average

return if they fail to deliver outputs or if they deliver them inefficiently’ [71]. Also, a key feature of the proposal is to promote CAPEX efficiency by extending the regulatory period (from 5 to 8 years), in order to incentivise longer decision making horizons.

4.1.3. Promoting innovation in a regulated sector

A notable feature of the UK regulator’s efforts to bring about system renewal and transition has been the introduction of specific incentives for innovation [7]. It was felt that an artificial innovation incentive was needed due to the fact that in a natural monopoly environment, innovation is unlikely to emerge as an outcome of conventional competitive processes. Similar problems will be faced in many infrastructure based sectors in the stagnation and inertia phase because, as described in Section 2, they tend to display natural monopoly features. Also, as the following quote from an energy company employee suggests, due to the RPI-x regulatory incentive structure, DNOs have tended to develop low risk business strategies with a conservative culture towards risk taking becoming embedded within their organisations:

‘I’m not sure (...) that we’re that big on innovation ourselves (...) we’re a utility that runs a business and a set of assets and those assets we buy from manufacturers, equipment manufacturers of one description or another’.

[Interview – Energy Company]

In 2005, Ofgem introduced an R&D funding mechanism – the Innovation Funding Incentive (IFI) – where each DNO was permitted to spend up to 0.5% of its regulated revenue on R&D which ‘allows a DNO to pass through to customers 80% (tapered from 90% to 70% from 2005 to 2010) of the cost of eligible IFI projects’ [72]. Along with the IFI, a measure to promote trials of network innovations was also introduced called Registered Power Zones (RPZ), where a DNO could spend up to £500,000/year and earn enhanced revenues for the connection of DGs. RPZ offered ‘an additional incentive of an extra £3/kW/year (over and above the main DG incentive) for a five year period commencing on the date of commissioning of the project’ [66], this was ‘capped at £0.5 million per DNO per year’ [67]. Although the introduction of a specific innovation mechanism was welcomed, there was a poor uptake by the DNOs, in part due to the lack of ambition of the scheme itself. One interviewee describes it as:

‘...a failure, there are only 3 schemes after 4 or 5 years. There’s no incentive for the network to try something [which] may undermine its business model’.

[Interview – Academia]

Whilst continuing the IFI, the regulator replaced the RPZ scheme with the Low Carbon Networks (LCN) Fund in 2010. Similar to the RPZ scheme, the aim of the LCN Fund is to ‘try to replicate the incentives on unregulated companies to innovate’ [70]. A significant difference however is that the LCN Fund is not confined to the connection of DG alone, but seeks to promote ANM more explicitly, in particular by incentivising collaboration between parties cross the value chain, e.g. between DNOs and retail companies who are installing domestic smart metres.

There are two tiers to the LCN Fund. The first tier of £80 million is for smaller projects, with funding per DNO being limited annually. These projects are registered with Ofgem and in both 2010 and 2011 nine projects have been registered as tier one projects. The second tier provides £320 million with Ofgem holding an ‘annual competition for project funding and the DNOs will compete against each other for an allocation of the funds’ [73]. Submissions are assessed by a panel of experts and each year a number of ‘flagship projects’ are awarded funding. There is also an ex-post ‘discretionary funding mechanism’ of £100 million which ‘enables Ofgem to reward successful delivery and projects that bring particular value in helping the DNOs understand what investment, commercial arrangements and operating strategies they should be putting in place to provide security of supply at value for money for future network users, whilst doing all they can to tackle climate change’ [73].

Although it is too early to assess whether the LCN Fund is a success, it has largely been welcomed within the industry and as part of the RIIO proposals a similar programme is planned for 2015, called the ‘Innovation Stimulus’ [73]. Innovation incentive schemes such as these are important not only in trialling new technologies associated with active distribution networks, but also in developing the capabilities and organisational routines necessary to promote innovation as a strategy within the network companies, which is necessary for system renewal and transition. Programmes such as the LNCF can begin to change this culture within the sector; however, it is envisioned that over time specific innovation incentive schemes will be ‘wound down’ and innovation will need to become part of the day to day planning and operation of the networks [73]. It is as yet unclear, however, as to the mechanisms and processes by which innovation can be institutionally embedded within the mainstream regulatory process.

4.2. Case #2: system building and expansion – city scale district energy schemes

Unlike electricity distribution networks, the development of city-scale district energy schemes involving combined heat and power with district heating (CHP/DH) is a largely unregulated area and thus represents an example of a local distribution system at an earlier phase of the infrastructure lifecycle. Today in the UK, as in most other developed nations, the vast majority of electricity is generated at large centralised generating stations and transported long distances via a high voltage transmission grid and regional distribution systems. District heating, on the other hand, is organised on the basis of networking hot water or steam within a locality via a piped distribution network connected to the pipes and radiators within buildings [77].

Despite the potential efficiency benefits, CHP/DH has not developed to the same scale in the UK as in other European countries [45]. Although some CHP/DH schemes are operating in cities such as Nottingham, Aberdeen, Birmingham and London, these are relatively small and dispersed niches accounting for only 2% of overall heat demand [76] and 1% of households [77]. Electrical power from CHP accounts for approximately 6% of total capacity, with 98% of this being stand-alone industrial plants and only 2% district heating [97]. This is in contrast to Scandinavian countries; for example in Finland and Denmark district heating

accounts for 49% and 60% of total supply respectively, and in Vienna 36% is supplied via heat pipes [76]. Strong local government involvement in coordinating a range of actors has been a significant feature of the diffusion of district heating in Scandinavian countries [87]; however, local authorities in the UK have had a more limited role energy planning and decision making [78,79]. A recent study [10] commissioned by DECC for its 2013 white paper: ‘The Future of Heating’ [21] identified a wide range of barriers to the development of local authority led heat networks, key amongst these are a lack of upfront funding for the initial capital cost of laying pipes, along with a lack of expertise and organisational capacity at a local level. However the report identified a wide range of their barriers, quoting from the report these include:

- Uncertainty regarding longevity and reliability of customer demand
- Uncertainty regarding reliable heat sources
- Lack of regulation and inconsistent pricing of heat
- Lack of generally accepted contract mechanisms
- Lack of a generally accepted and established role for local authorities
- Choice of heating system
- Skill gaps
- Access to land
- Tax and business rates
- Air quality approval.

Following a brief overview of the role of local authorities, we discuss in more depth how creating new alignments of technology, organisational change and financing are particularly important in overcoming some of these systemic barriers.

4.2.1. Local authorities and CHP/DH in the UK

There are a relatively small but growing number of local authorities in the UK actively involved in developing and expanding CHP/DH schemes within their localities. As part of our study we have observed that, for a number of reasons, some councils are looking towards DE and CHP/DH as a long term strategy to engage with the emerging sustainability and climate change agendas (cities and large towns in this category include: Southampton, Woking, London, Birmingham, Leicester, Nottingham, Sheffield and Aberdeen) [8]. In part, this has been enabled by recent changes to legislation regarding the relationship between national and local governments. For example, following the introduction of the Local Government Act and the Sustainable Communities Act in 2000 and 2007 respectively, local authorities have gained new forms of functional and financial autonomy in this area – in particular the ‘power to do anything which they consider is likely to achieve’ economic, social and environmental well-being in their area including incurring expenditure [14].

Enabled by these legislative changes and prompted by rising energy prices and fuel poverty rates, councils have begun to take a more direct role in efforts to reduce the fuel bill of both the council itself and tenants in social housing. This is particularly the case within large city councils, often in former industrialized cities in the north of England e.g. Sheffield and Nottingham, and in densely populated inner city areas with a large social housing stock e.g. London and Aberdeen. Another significant motivating factor behind local authority involvement in the development of CHP/DH has been to promote low carbon development within

their localities. Some of the councils are keen to use CHP/DH to attract new developments; for example, within Woking Borough areas of the town have been zoned and potential developers are incentivized to invest by the council offering connection to its district heating network.

4.2.2. *Instigating organisational change at the local level*

Due to the fact that councils have traditionally not had a prominent role in energy planning in the UK, they tend to lack the organisational capacity necessary to develop and expand DE schemes. Developing local energy infrastructures requires a degree of coordinated change across a number of council departments, such as planning, building services, finance, legal and procurement: this level of institutional flexibility tends not to be a feature of such large public sector organisations. A common feature across councils that have been successful in developing and expanding DE schemes has been the presence of district heating ‘champions’ who are key to bringing about the necessary coordinated and systemic change – similar to Thomas Hughes’ system builders [47]. These are highly motivated and knowledgeable individuals who carry out various functions including coordinating actors across a number of council departments, engaging with a range of external actors, and promoting the financial, social and environmental benefits of CHP/DH within the council chamber. From our interviews, we have identified two types of champion which have been associated with successful DE schemes – technical champions and political champions (see Table 2 below). A technical champion, typically an employee of a council energy or building services department, possess the technical knowledge and capabilities required to develop CHP/DH, can learn from best practice both nationally and internationally and has project management skills. A political champion, on the other hand, as one interviewee notes, gets the issue ‘elevated up through the organisation and get it right at the top, that high level buy-in’ (interviewee – Local Authority). CHP/DH, being a large scale and risky investment, requires long term commitment, and this is particularly difficult in a political environment. The central role of a political champion, in some cases an elected official, is outlined by the following interviewee who works on the technical side of a DE scheme. The quote emphasises the importance of promoting long term stability in an environment where the power dynamics within the council are constantly in flux:

“He bought in to the scheme very early on, he came on the visits with us [and] we went to look at other local authorities (...) and he bought in, so we have (...) buy in

at that high level. One of the things that helps drive that through was when, and you do get barriers to certain things like this, people say; ‘is it right having 25 year contracts’. You will always get the skeptics”.

[Interview – Local Authority]

Securing a level of alignment between the technical (bottom up) and political (top down) processes has been key in successful schemes. In the case of Woking Council, a leader in this area, the council Chief Executive who was involved in developing the energy strategy of the council since its inception, argues that ‘it’s a combination of political and technical, managerial’ requiring ‘strong political leadership and direction, managerial support and technical support. And if you can’t get those three aligned it doesn’t work’ (Interview – Local Authority).

4.2.3. *Aligning finance with technical innovation*

A second key institutional challenge in developing and expanding CHP/DH is that of financing what are relatively large infrastructure investments in cities. Due to the expense involved in laying distribution pipes, the upfront capital costs are substantial for CHP/DH (Laying pipes costs in the region of £1000/m). Securing project financing at a reasonable cost-of-capital can be difficult for DE for a number of reasons: the long payback period on investment, the lack of expertise in CHP/DH in the UK [76], the long lead times involved in planning and delivering major infrastructure projects, and the fact that financial institutions in the UK have tended to be reluctant to invest in low carbon capital projects [60]. To date, the main source of funding for CHP/DH has been through a range of grant schemes; however, the rapidly evolving energy policy environment in recent years has meant that these funding streams are temporary, thus undermining the long term certainty required for infrastructure investments. The following excerpt from an interview with a private CHP/DH operator illustrates that this has undermined investor confidence in the long term commercial viability of district heating:

“What we have seen is that support mechanisms often disappear without a trace very quickly and with little warning and that has led to schemes being pulled at the last minute where funding disappears and can be quite an unsustainable practice”.

[Interview – DE Operator]

Developing an organisational structure with contractual arrangements in place which reflect the level of risk that a

Table 2
The key functions of technical and political champions.

Technical champion	Political champion
<ul style="list-style-type: none"> • Improve decentralized energy knowledge base and capacity of the building services/energy management department • Learn from other successful schemes both nationally and internationally • Coordinate actors from a number of council departments • Scope out the potential demand for heating within the locality and develop an overall strategic vision for the expansion of the scheme • Manage the contractual arrangements for the building and operation of the scheme 	<ul style="list-style-type: none"> • Place CHP/DH on the political agenda • Enrol other councillors from across the political spectrum and create an advocacy coalition • Help to de-risk large scale investments by displaying a commitment to long term infrastructure development regardless of the political cycle • Use CHP/DH to advance the sustainability/low carbon agenda and raise the profile of the council

council is willing to take on is key. There are a number of options available to councils including own funding where a capital fund is build up, perhaps from efficiency savings, over a number of years and re-invested in DH pipes. This can be combined with capital grants, and in a number of the cases, these capital grants are used alongside own funding to initiate projects. Another option is to enter into a long term energy services contract with a private sector partner [42,44]. Here, the council acts as the anchor tenant around which the operator can expand a scheme throughout a city. This private sector model is attractive as, depending on the contractual arrangements in place, it transfers much of the investment and operational risk to the private sector, as the prices paid for energy services by the council will be index-linked over the period. However, there are disadvantages: the required rate of return on new investments will likely be higher in this case, and because the private operator controls the operation and evolution of the system, there will be less scope for a local authority to integrate the CHP/DH scheme into their wider energy and climate change strategies.

5. Discussion of governance strategies for infrastructure transition

As highlighted by our cases, the governance of energy distribution networks is becoming increasingly complex with policy makers and regulators having to deal with a multitude of challenges along the infrastructure lifecycle. This, we argue, will necessitate a move away from the traditional emphasis on achieving short term efficiencies in the operation of incumbent networks, towards a more dynamic model based on a socio-technical understanding which can address governance challenges at the different phases of transition. The infrastructure lifecycle model based on a cyclical and dynamic understanding of socio-technical systems provides a framework to understand these different phases of infrastructure change:

For the case of an incumbent system like electricity distribution which needs to move into a *renewal and transition* phase, it is clear that the role of the regulator remains central. It will need to align its activities in a coherent manner with broader energy policy trends such as renewable generation and emissions reductions targets. This, however, presents challenges, since in a liberalised environment, the independence of sector regulators from government interference has been emphasised. A key challenge for the regulator in this new context of *system renewal and transition* will be to balance the interests of customers and shareholders whilst promoting risk taking and transformation, and at the same time maintaining quality standards. The case of electricity distribution in the UK shows how the UK regulator has begun to engage with this task by introducing incentives for long term investment horizons and CAPEX efficiency, whilst shifting its emphasis towards the regulation of specified performance outputs.

A second issue facing incumbent sectors is a lack of innovation. Innovation is central to the development of long term investment strategies, the optimal utilisation of the existing asset base and the integration of various low carbon technologies. However, innovation in these sectors is less likely as they are currently locked-in to an established technological trajectory which has been reinforced by the regulatory framework and the strategies of incumbent actors. Also, they do not operate in a competitive environment as would be the

case in conventional sectors. Therefore, being regarded as natural monopolies, network companies are unlikely to engage in innovation as a response to an external competitive threat and they must therefore be either incentivised or mandated to do so through the actions of the regulator. The UK regulator has been to the forefront of designing specific incentives for innovation and their experience should have valuable lessons for other regulators. However, because this process is at a relatively early stage, it remains to be seen how a separate incentive mechanism can be incorporated into the mainstream regulatory process and the day-to-day organisational routines of the network operators.

The phase of *system building and establishment* poses a different set of questions, as highlighted by the challenges facing CHP/DH in the UK. These systems develop in local contexts, often removed from national level energy institutions, and therefore tend to lack a supporting institutional framework for their expansion. As a result, CHP/DH currently relies on motivated individuals who are acting in specific local contexts and as such the sector is quite fragmented and dispersed. It is clear from the discussion that along with increasing the resources available to local authorities, the development of knowledge and capacities for learning at the local level is essential. Combined with this, diffusing CHP/DH more widely will necessitate the development of a more coherent and robust set of sector level institutions which can disseminate best practice and reduce transaction costs. Also, the experience of Nordic countries illustrates the importance of significant government intervention in creating a favourable selection environment for CHP/DH. In Denmark, for example, the government introduced legislation which imposed a ban on waste heat and mandated connection to a heating network where it exists. It also changed its electricity market structure in order to explicitly recognise the environmental and system benefits of CHP/DH [98]. The UK has however traditionally adopted technology neutral energy policies and sought to avoid ‘picking winners’; i.e. explicitly favouring certain technologies over others. However, this strategy has been challenged on the grounds that in order to influence longer term transition processes and promote the diffusion of promising low carbon niches such as CHP/DH, governments need to take a more active role in setting priorities and directing change, particularly if there is a high degree of uncertainty in carbon and energy markets [28,32,61,93].

Each of the cases highlight the fact that infrastructure transitions cannot be considered purely in technical terms, but rather as a coevolutionary process involving interactions between technologies, institutions, infrastructure users, business strategies and wider ecosystem change [27]. Due to the fact that infrastructures have public good characteristics, the role of bodies such as the sector regulator, local authorities and government is central to developing a synergistic and mutually beneficial relationship between these elements.

Thinking beyond the particular cases of electricity and heat distribution in the UK, there may be some more generalizable insights here for other infrastructures which will be important enablers for a low carbon transition. In table 3 below, we summarise how our main findings from the cases might be applicable to low carbon infrastructures in other sectors. Established national infrastructures such as gas supply and

electricity transmission, although technically and operationally distinct, as regulated incumbent systems will face similar types of challenges in moving into a *renewal and transition* phase. For example, decarbonisation of the gas grid in a low carbon future may see increasing use of the existing infrastructure to transport biomethane and/or hydrogen [23], whilst new investments in electricity transmission networks will be required to access remote renewable resources and to interconnect with neighbouring markets to deal with concerns over intermittency of renewables [63]. On the other hand, the development of entirely new networks such as CO₂ transport pipelines for carbon capture and storage technology, battery recharging infrastructure for electric vehicles and hydrogen transport and storage are at a nascent stage. Key issues to be addressed here in *system building and establishment* and moving into the *expansion and momentum* phase will be the development of local organisational capacity and expertise along with financing mechanisms which help to overcome early stage project risks (See Table 3).

An area for future research will be to conduct a cross-case analysis of these different infrastructure sectors to think through the technical, institutional and organisational similarities and differences, exploring implications for policy and governance. Also, as progress is made towards low carbon energy it is likely that complex interdependencies between the electricity, transport and heat sectors will emerge which will of course have implications at an organisational and institutional level. For example, new demands will be placed on the gas infrastructure as electricity generation from gas is phased out and only used as peaking plant during periods of low wind and high demand. Also, as we touched upon in Section 4.1, the increasing electrification of the heat and transport sectors will require active management of electricity distribution networks to incorporate heat pumps and electric vehicles alongside distributed generation technologies.

We argue that the socio-technical approach presented in Section 3 can provide useful analytical tools to address these complex issues and provides the basis for a framework that

can be employed across these different sectors, helping to better enable cross-sector learning.

6. Conclusions

This paper discussed the processes and mechanisms of infrastructure transition from a socio-technical systems perspective, focusing on electricity and heat distribution networks in the UK. Our purpose was to contribute to recent debates regarding the role and importance of infrastructure networks to broader sustainability transitions in the energy, water and mobility sectors [33,57]. Traditionally the focus of governance has been on reducing the cost of operating incumbent infrastructures, and existing policy and regulatory processes have only recently begun to consider how to transform these systems. The issue of how to develop and expand the new infrastructures necessary for the low carbon transition has received even less attention. We proposed that along an infrastructure lifecycle different governance strategies will need to be employed by policy makers and regulators to address the key governance challenges faced at different phases, particularly relating to the *system renewal and transition*, and *system building and establishment stages*.

In order to develop our arguments, we discussed the cases of electricity and heat distribution in the UK, which exemplify the challenges at these different stages. These distribution networks will be key to facilitating the development of a low carbon energy system; for example, by enabling the integration of renewable technologies, improving energy efficiency and enabling demand side management. We observed how recent efforts to transform these infrastructure networks have encountered a number of institutional challenges at different phases of the infrastructure lifecycle: in the case of electricity distribution, which needs to move from *stagnation and inertia* moving into a *renewal and transition phase*, the sector regulator has sought to overcome the barriers to long term investment and innovation, whilst in the case of district heating, which faces multiple barriers in the transition from *system building and establishment* into *expansion and momentum*, local authorities have struggled to finance large scale infrastructure investments and develop

Table 3
Lessons for governing infrastructure transitions from UK case studies.

Transition phase	Stagnation and inertia moving into renewal and transition	System building and establishment moving into expansion and momentum
Examples of low carbon infrastructure	<ul style="list-style-type: none"> • Smart grids/active distribution networks, • Electricity transmission for renewable resources and development of international 'Supergrids' • More flexible natural gas pipeline infrastructure 	<ul style="list-style-type: none"> • City wide district heating (UK) • hydrogen transport & storage • CO₂ transport and storage
Key governance challenges	<ul style="list-style-type: none"> • Short term investment horizons • Focus on 'sweating the assets' • Lack of innovation and risk averse business culture • Lack of a competitive threat for large network operators to develop business strategies based on innovation 	<ul style="list-style-type: none"> • Electric vehicle recharging infrastructure • Lack of supporting institutional structure for geographically dispersed niches • High rates of return demanded on investment capital • Lack of local level leadership and coordination • Underdeveloped technical and organisational capacity at the local level.
Governance strategies	<ul style="list-style-type: none"> • Specific incentives for R&D and demonstration projects • Extend regulatory review periods • Closer scrutiny of business plans and investment proposals • Balance incentives for OPEX and CAPEX efficiency • Move towards outputs based regulation 	<ul style="list-style-type: none"> • Stronger government intervention in the market to support emerging technologies • Develop collaborative platforms for sharing best practice and knowledge exchange • Create incentives for system builders and reward initiative • Provide a stable investment environment e.g. by government underwriting loans

the necessary technical and organisational capacity at the local level.

Overall however progress in this area has been piecemeal, largely due to fragmented sector structures and a lack of clear and consistent overarching framework for low carbon infrastructure governance. Developing a more nuanced understanding of the dynamics of socio-technical innovation in these infrastructure based sectors and recognising that governance interventions will need to be more targeted is perhaps a prerequisite to addressing this.

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References

- [1] W.J. Abernathy, K.B. Clark, Innovation: mapping the winds of creative destruction, *Res. Policy* 14 (1985) 3–22.
- [2] S. Arapostathis, A. Carlsson-Hyslop, P.J.G. Pearson, J. Thornton, M. Gradillas, S. Laczay, S. Wallis, Governing transitions: cases and insights from two periods in the history of the UK gas industry, *Energy Policy* 52 (2013) 25–44.
- [3] Berr, UK Renewable Energy Strategy Consultation Document. Department for Business, Enterprise & Regulatory Reform, London, 2008.
- [4] W.B. Bijker, *Of Bicycles, Bakelite and Bulbs: Toward a Theory of Sociotechnical Change*, MIT Press, Cambridge MA, 1995.
- [5] W.E. Bijker, J. Law, Do technologies have trajectories? in: W.E. Bijker, J. Law (Eds.), *Shaping Technology/Building Society*, MIT Press, Cambridge MA, 1992.
- [6] R. Bolton, *Socio-technical Transitions and Infrastructure Networks: The Cases of Electricity and Heat Distribution in the UK*, (PhD Thesis) School of Earth and Environment, University of Leeds, 2011.
- [7] R. Bolton, T. Foxon, Governing infrastructure networks for a low carbon economy: co-evolution of technologies and institutions in UK electricity distribution networks, *Compet. Regul. Netw. Ind.* 12 (2011) 2–26.
- [8] R. Bolton, T. Foxon, Urban infrastructure dynamics: market regulation and the shaping of district energy in UK cities, *Environ. Plann. A* 45 (2013) 2194–2211, <http://dx.doi.org/10.1068/a45575>.
- [9] R. Bolton, A. Hawkes, Infrastructure, investment and the low carbon transition, in: C. Mitchell, J. Watson, J. Whiting (Eds.), *New Challenges in Energy Security: The UK in a Multipolar World*, Palgrave MacMillan, 2013.
- [10] BRE, University Of Edinburgh & Centre For Sustainable Energy, Research into barriers to deployment of district heating networks, Research Study by BRE, University of Edinburgh and the Centre for Sustainable Energy for the Department of Energy & Climate Change, London, 2013.
- [11] Ccc, *Building a Low-carbon Economy: The UK's Contribution to Tackling Climate Change*, Committee on Climate Change, London, 2008.
- [12] Ccc, *The Fourth Carbon Budget Reducing Emissions Through the 2020s*, Committee on Climate Change, London, 2010.
- [13] O. Coutard, Introduction: the evolving forms of governance of large technical systems, in: O. Coutard (Ed.), *The Governance of Large Technical Systems*, Routeledge, London, 1999.
- [14] Dclg, *Local Government Act 2000*, Department for Communities and Local Government, London, 2000.
- [15] Decc, *Heat and Energy Saving Strategy Consultation*, 2009.
- [16] Decc, *Heat and Energy Saving Strategy Consultation*, Department of Energy and Climate Change, London, 2009.
- [17] Decc, *Smarter Grids: The Opportunity*, Department of Energy and Climate Change, London, 2009.
- [18] Decc, *Renewable Heat Incentive*, Department of Energy and Climate Change, London, 2011.
- [19] Decc, *Energy Security Strategy*, Department of Energy and Climate Change, London, 2012.
- [20] Decc, *Digest of United Kingdom Energy Statistics 2013*, Department of Energy and Climate Change, London UK, 2013.
- [21] Decc, *The Future of Heating: Meeting the Challenge*, Department of Energy and Climate Change, London, 2013.
- [22] P. Djapic, C. Ramsay, D. Pudjianto, G. Strbac, J. Mutale, N. Jenkins, R. Allan, Taking an active approach, *IEEE Power Energ. Mag.* 5 (2007) 68–77.
- [23] P.E. Dodds, W. McDowall, The future of the UK gas network, *Energy Policy* 60 (2013) 305–316.
- [24] G. Dosi, Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change, *Res. Policy* 11 (1982) 147–162.
- [25] Eu, *SmartGrids Vision and Strategy for Europe's Electricity Networks of the Future*, European Technology Platform, Brussels, 2006.
- [26] M. Finger, J. Groenewegen, R. Künneke, The quest for coherence between institutions and technologies in infrastructures, *J. Netw. Ind.* 6 (2005) 227–259.
- [27] T. Foxon, A coevolutionary framework for analysing a transition to a sustainable low carbon economy, *Ecol. Econ.* 70 (2011) 2258–2267.
- [28] T. Foxon, P. Pearson, Overcoming barriers to innovation and diffusion of cleaner technologies: some features of a sustainable innovation policy regime, *J. Clean. Prod.* 16 (2008) S148–S161.
- [29] T.J. Foxon, Transition pathways for a UK low carbon electricity future, *Energy Policy* 52 (2013) 10–24.
- [30] T.J. Foxon, R. Gross, A. Chase, J. Howes, A. Arnall, D. Anderson, UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures, *Energy Policy* 33 (2005) 2123–2137.
- [31] T.J. Foxon, G.P. Hammond, P.J.G. Pearson, Developing transition pathways for a low carbon electricity system in the UK, *Technol. Forecast. Soc. Chang.* 77 (2010) 1203–1213.
- [32] T.J. Foxon, P.J.G. Pearson, Towards improved policy processes for promoting innovation in renewable electricity technologies in the UK, *Energy Policy* 35 (2007) 1539–1550.
- [33] N. Frantzeskaki, D. Loorbach, Towards governing infrasystem transitions: reinforcing lock-in or facilitating change? *Technol. Forecast. Soc. Chang.* 77 (2010) 1292–1301.
- [34] C. Freeman, Diffusion: the spread of new technology to firms, sectors and nations, in: A. Heertje (Ed.), *Innovation, Technology, and Finance*, Basil Blackwell, New York, 1988.
- [35] C. Freeman, F. Louçã, *As Time Goes By: From the Industrial Revolutions to the Information Revolution*, Oxford University Press, Oxford, 2001.
- [36] Frontier, *The Role of Future Energy Networks: A Report Prepared for Ofgem*, Frontier Economics, London, 2010.
- [37] F. Geels, Co-evolution of technology and society: the transition in water supply and personal hygiene in the Netherlands (1850–1930) – a case study in multi-level perspective, *Technol. Soc.* 27 (2005) 363–397.
- [38] F. Geels, *Technological Transitions and System Innovations: A Co-evolutionary and Socio-technical Analysis*, Edward Elgar, 2005.
- [39] F.W. Geels, Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study, *Res. Policy* 31 (2002) 1257–1274.
- [40] F.W. Geels, J. Schot, Typology of sociotechnical transition pathways, *Res. Policy* 36 (2007) 399–417.
- [41] D. Giannakis, T. Jamasb, M. Pollitt, Benchmarking and incentive regulation of quality of service: an application to the UK electricity distribution networks, *Energy Policy* 33 (2005) 2256–2271.
- [42] M.J. Hannon, T.J. Foxon, W.F. Gale, The co-evolutionary relationship between Energy Service Companies and the UK energy system: implications for a low-carbon transition, *Energy Policy* 61 (2013) 1031–1045.
- [43] T. Hargreaves, M. Nye, J. Burgess, Making energy visible: a qualitative field study of how householders interact with feedback from smart energy monitors, *Energy Policy* 38 (2010) 6111–6119.
- [44] D. Hawkey, J. Webb, M. Winskel, Organisation and governance of urban energy systems: district heating and cooling in the UK, *J. Clean. Prod.* 50 (2013) 22–31.
- [45] D.J.C. Hawkey, District heating in the UK: a Technological Innovation Systems analysis, *Environ. Innov. Soc. Transitions* 5 (2012) 19–32.
- [46] D. Helm, *Energy, the State, and the Market: British Energy Policy Since 1979*, Oxford University Press, Oxford, 2004.
- [47] T. Hughes, *Networks of Power: Electrification in Western Society, 1880–1930* Baltimore, Johns Hopkins University Press, 1983.
- [48] T.P. Hughes, *The Evolution of Large technical Systems*, in: W. Bijker, T.P. Hughes, T. Pinch (Eds.), *The Social Construction of Technical Systems*, MIT Press, Cambridge Massachusetts, 1987.
- [49] T. Jamasb, M. Pollitt, Incentive regulation of electricity distribution networks: Lessons of experience from Britain, *Energy Policy* 35 (2007) 6163–6187.
- [50] T. Jamasb, M. Pollitt, Liberalisation and R&D in network industries: The case of the electricity industry, *Res. Policy* 37 (2008) 995–1008.

- [51] T. Jamasb, M.G. Pollitt, Electricity sector liberalisation and innovation: An analysis of the UK's patenting activities, *Res. Policy* 40 (2011) 309–324.
- [52] A. Kaijser, The dynamics of infrasystems. Lessons from history, Proceedings of the 6th International Summer Academy on Technology Studies – Urban Infrastructure in Transition, 2004.
- [53] S. Kelly, M. Pollitt, An assessment of the present and future opportunities for combined heat and power with district heating (CHP-DH) in the United Kingdom, *Energy Policy* 38 (2010) 6936–6945.
- [54] S. Klepper, *Industry Life Cycles*, Ind. Corp. Chang. 6 (1997) 145–182.
- [55] R.W. Künneke, Electricity networks: how 'natural' is the monopoly? *Util. Policy* 8 (1999) 99–108.
- [56] R.W. Künneke, Institutional reform and technological practice: the case of electricity, *Ind. Corp. Chang.* 17 (2008) 233–265.
- [57] D. Loorbach, N. Frantzeskaki, W. Thissen, Introduction to the special section: infrastructures and transitions, *Technol. Forecast. Soc. Chang.* 77 (2010) 1195–1202.
- [58] J. Markard, Transformation of infrastructures: sector characteristics and implications for fundamental change, *J. Infrastruct. Syst.* 17 (2011).
- [59] J. McDonald, Adaptive intelligent power systems: active distribution networks, *Energy Policy* 36 (2008) 4346–4351.
- [60] C. Mitchell, *The Renewable Non-fossil Fuel Obligation: A Case Study of the Barriers to Energy Technology Development*, (PhD Thesis) SPRU, University of Sussex, 1994.
- [61] C. Mitchell, *The Political Economy of Sustainable Energy*, Palgrave Macmillan, New York, 2008.
- [62] C. Mitchell, B. Woodman, Regulation and sustainable energy systems, in: R. Baldwin, M. Cave, M. Lodge (Eds.), *The Oxford Handbook of Regulation*, OUP, Oxford, 2010.
- [63] National GRID, *Operating the Electricity Transmission Networks in 2020 – Update June 2011*, National Grid PLC, Warwick, 2011.
- [64] S.O. Negro, M.P. Hekkert, R.E. Smits, Explaining the failure of the Dutch innovation system for biomass digestion: a functional analysis, *Energy Policy* 35 (2007) 925–938.
- [65] M. Nye, L. Whitmarsh, T. Foxon, Socio-psychological perspectives in the active roles of domestic actors in transition to a lower carbon electricity system, *Environ. Plann.* A 42 (2009) 697–714.
- [66] Ofgem, *Electricity Distribution Price Control Review: Final Proposals*, Office of Gas and Electricity Markets, London, 2004.
- [67] Ofgem, *Further Details of the RPZ Scheme: Guidance Document Office of Gas and Electricity Markets*, London, 2005.
- [68] Ofgem, *Electricity Distribution Price Control Review: Final Proposals*, Office of Gas and Electricity Markets, London, 2009.
- [69] Ofgem, *Regulating Energy Networks for the Future: RPI-X@20 Principles, Process and Issues*, 2009.
- [70] Ofgem, *LCN Fund Governance Document v.3*, Office of Gas and Electricity Markets, London, 2010.
- [71] Ofgem, *Regulating Energy Networks for the Future: RPI-X@20 Emerging Thinking*, Office of Gas and Electricity Markets, London, 2010.
- [72] Ofgem, *Reports by Distribution Network Operators (DNOs) on Innovation Funding Incentive (IFI) and Registered Power Zone (RPZ) Activity for 2008–2009*, Office of Gas and Electricity Markets, London, 2010.
- [73] Ofgem, *RIO: A New Way to Regulate Energy Networks*, Final Decision, Office of Gas and Electricity Markets, London, 2010.
- [74] Ofgem, *Electricity Capacity Assessment*, Office of Gas and Electricity Markets, London, 2012.
- [75] T. Pinch, W. Bijker, The Social Construction of Facts and Artifacts: Or How the Sociology of Technology Might Benefit Each Other, in: T. Pinch, W. Bijker, T. Hughes (Eds.), *The Social Construction of Technical Systems*, MIT Press, Cambridge, 1987.
- [76] Pöyry, *The Potential and Costs of District Heating Networks*, PÖYRY Consultants, London, 2009.
- [77] S. Roberts, Infrastructure challenges for the built environment, *Energy Policy* 36 (2008) 4563–4567.
- [78] S. Russell, *The Political Shaping of Energy Technology: Combined Heat and Power in Britain*, (PhD Thesis) University of Aston, UK, 1986.
- [79] S. Russell, Writing energy history: explaining the neglect of CHP/DH in Britain, *Br. J. Hist. Sci.* 26 (1993) 33–54.
- [80] S. Russell, R. Williams, Social shaping of technology: frameworks, findings and implications for policy with glossary of social shaping concepts, in: K. Sorensen, R. Williams (Eds.), *Shaping Technology, Guiding Policy: Concepts, Spaces and Tools*, Elgar, Cheltenham, 2002.
- [81] R. Shaw, M. Attree, T. Jackson, M. Kay, The value of reducing distribution losses by domestic load-shifting: a network perspective, *Energy Policy* 37 (2009) 3159–3167.
- [82] A. Smith, A. Stirling, F. Berkhout, The governance of sustainable socio-technical transitions, *Res. Policy* 34 (2005) 1491–1510.
- [83] G. Strbac, Demand side management: benefits and challenges, *Energy Policy* 36 (2008) 4419–4426.
- [84] G. Strbac, C.K. Gan, M. Aunedi, V. Stanojevic, P. Djapic, J. Dejvises, P. Mancarella, A. Hawkes, D. Pudjiant, *Benefits of Advanced Smart Metering for Demand Response Based Control of Distribution Networks*, 2010.
- [85] G. Strbac, N. Jenkins, T. Green, D. Pudjiant, *Review of Innovative Network Concepts*, European Commission, Directorate-General for Energy and Transport, 2006.
- [86] G. Strbac, C. Ramsay, R. Moreno, This Sustainable Isle, *IEEE Power Eng. Mag.* 7 (2009) 44–52.
- [87] J. Summerton, *District Heating Comes to Town: The Social Shaping of an Energy System*, Linköping Studies in Arts and Science, Linköping, 1992.
- [88] J. Summerton, *Introductory Essay: The Systems Approach to Technological Change*, in: J. Summerton (Ed.), *Changing Large Technical Systems*, Westview Press, Boulder, 1994.
- [89] P.G. Taylor, R. Bolton, D. Stone, P. Upham, Developing pathways for energy storage in the UK using a coevolutionary framework, *Energy Policy* 63 (2013) 230–243.
- [90] Ukgbc, *Sustainable Community Infrastructure: A Joint Report by the UK Green Building Council and the Zero Carbon Hub*, 2010.
- [91] G.C. Unruh, Understanding carbon lock-in, *Energy Policy* 28 (2000) 817–830.
- [92] G. Verbong, F. Geels, The ongoing energy transition: lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004), *Energy Policy* 35 (2007) 1025–1037.
- [93] J. Watson, *Setting Priorities in Energy Innovation Policy: Lessons for the UK*. Discussion Paper 2008-08, Cambridge, Mass.: Belfer Center for Science and International Affairs, August 2008, 2008.
- [94] R. Williams, Introduction, in: K. Sørensen, R. Williams (Eds.), *Guiding Policy, Shaping Technology: Concepts, Spaces and Tools*, Edward Elgar, London, 2002.
- [95] R. Williams, D. Edge, The social shaping of technology, *Res. Policy* 25 (1996) 865–899.
- [96] B. Woodman, P. Baker, Regulatory frameworks for decentralised energy, *Energy Policy* 36 (2008) 4527–4531.
- [97] S. Kelly, M. Pollitt, An assessment of the present and future opportunities for combined heat and power with district heating (CHP-DH) in the United Kingdom, *Energy Policy* 38 (2010) 6936–6945.
- [98] D. Toke, A. Fragaki, Do liberalised electricity markets help or hinder CHP and district heating? The case of the UK, *Energy Policy* 36 (2008) 1448–1456.

Dr. Ronan Bolton is a Lecturer in Science Technology and Innovation Studies at the University of Edinburgh. His research examines the governance and regulation of energy infrastructures and the design and functioning of energy markets. This paper is an output of his PhD research which was undertaken at the University of Leeds.

Dr. Timothy Foxon is a Reader in Sustainability and Innovation, and Research Councils UK Academic Fellow in the Sustainability Research Institute, School of Earth and Environment at the University of Leeds, and a member of the ESRC Centre for Climate Change Economics and Policy. His research explores technological and social factors relating to innovation and up-take of new energy technologies and analysis of the co-evolution of technologies, institutions and business strategies for a transition to a sustainable low carbon economy.