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The role of governance in accelerating transition towards more integrated, service-oriented infrastructure operation

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Abstract

Infrastructure operation in the UK can be described as separate utility systems provisioning unconstrained demand, with higher throughput corresponding to higher profits. A more sustainable approach would prioritise coordinated infrastructure operation focused on essential service delivery at the lowest possible resource use. However, the presiding policy paradigm reinforces the current regime to such an extent that it constrains the necessary transition to a more sustainable infrastructure system.

This paper combines the findings of existing case study research with insights from theories of multi-level governance, co-evolution and institutional dynamics to improve our understanding of how governance systems could accelerate the transition to more resource efficient, service-oriented infrastructure operation.

We develop a governance analysis framework to improve the understanding of this transition and in particular the role that governance might take in managing its acceleration. The framework allows analysts to identify elements or relationships that are absent from a system of interest or that are constrained by the current governance system. This can be used to identify alternative approaches to governance that remove barriers to transitions or enable the creation of a necessary element and accelerate desirable transitions.

1. Introduction

Our physical infrastructure – the system of energy, transport, communication, water, waste and flood protection assets – is a means to an end; it is built, maintained and expanded in order to enable the functioning of society and the economy. However, current infrastructure systems are ageing and cannot provide the adaptable, low carbon services required to respond to demographic and climatic change (CST 2009a). Sustainable, secure and equitable infrastructure systems will require rapid, systemic transformation of both physical and institutional systems.

The present form of infrastructure operation can be described as separate utility supply systems provisioning unconstrained demand, with higher throughput volumes corresponding to larger economic revenue. Furthermore there is often little incentive for end-user savings, for example in the UK, the majority of water and waste services are unmetered. This is both risky and ultimately unsustainable. Unlimited growth in demand means unlimited pressures on ecosystems and natural resources; at a time when we are already well beyond our planetary safe operating space (Rockström et al. 2009). From the perspective of societal resilience and security of supply, a system which understands and manages demand is much more secure than one of unlimited dependence on external, most often imported and sometimes scarce, inputs (Foresight 2011).

There has been extensive research into technology improvements or behaviour changes that could result in joint resource and cost savings (Cullen, Allwood, and Borgstein 2011; Lovins 1985). However, despite such cost-saving technologies and resource efficiencies existing, they are not implemented as part of the business-as-usual incentives of market economies (Cullen, Allwood, and Borgstein 2011). Furthermore, innovation and adoption of demand management (end-use) technologies tends to be marginalised in comparison with supply side (generation) technology (Wilson et al. 2012). A new approach is needed to accelerate adoption of resource efficient technologies and behaviours.

One approach proposed to overcome many of the barriers to efficiency is the idea of a "performance economy" or "functional economy" (Mont and Tukker 2006; Stahel 2010; Steinberger, van Niel, and Bourg 2009). In parallel, similar ideas developed from the business and marketing perspective (Grönroos 2011; Vargo and Lusch 2008). These ideas require a fundamental shift: away from selling products or metered quantities of infrastructure products (such as electricity, gas or water), and towards selling "services": which can be defined as the ultimate goal of the product or utility purchase (such as thermal comfort, illumination or motive power). Studies investigating Energy Service Companies (ESCos) agree on the beneficial nature of ESCo operation for the implementation of energy and cost-efficient technologies (Hannon, Foxon, and Gale; Westling 2003; Marino, Bertoldi, and Rezessy 2010; Sorrell 2007). However, they also agree on the huge obstacles to mainstreaming the ESCo business model, from regulation to lack of information and training to risk sharing. Left to the market, the adoption of these business models has lagged behind expectations (Bertoldi, Rezessy, and Vine 2006). Despite this there has been little work investigating how governance could help to overcome these obstacles or support the transfer of the energy service model to other infrastructures.

Infrastructure is becoming more integrated physically, operationally and digitally, which can leave it more vulnerable to failure (Rinaldi, Peerenboom, and Kelly 2001; Zimmerman and Restrepo 2006). Importantly, operating infrastructure systems in silos, despite this increasing integration, leads to "*financial and operational inefficiencies, a poorer service to citizens and businesses, and unintended negative consequences"* (CST 2009a). This inefficiency becomes particularly apparent when one considers infrastructure services integration at the end user level; one service may rely on multiple infrastructure systems. Indeed, the end-user, through technological and behavioural choices, is responsible for key performance aspects of infrastructure integration. There is a nascent body of work investigating the challenges and opportunities of physical infrastructure interconnections within the supply system (Hall et al. 2012; Frontier Economics 2012). However, little emphasis has been placed on integration of infrastructure at the end user or on integration in operation and governance.

To address these challenges we need alternative infrastructure operation configurations which are: centred on the end-user and their demand for services; concerned with implementing resource efficiency improvements; and take into account multiple utility streams simultaneously. We call these alternative configurations Multi-Utility Service Companies or MUSCos.

MUSCos represent a significant transition from mainstream infrastructure operation and are unlikely to occur at scale as a result of the current market-driven approach to regulation. An alternative governance paradigm is required to encourage and enable the radical change necessary to support the adoption of MUSCos. However, infrastructure can be described as socio-technical systems as it is a complex, interconnected system of technology embedded in society and interacting with public and private institutions (Unruh 2000). There is an emerging literature related to transition management: the governance of socio-technical transition (Fischer-Kowalski & Rotmans, 2009; Foxon, 2012; Shove & Walker, 2010; Smith, Stirling, & Berkhout, 2005). This recognises the need to consider the co-evolution of technology, end-users, businesses and institutions and their causal interactions (Foxon 2011). This has yet to be applied to alternative business models, across infrastructure streams, such as MUSCos.

MUSCos could manifest themselves at a many different scales, which will demand a more co-ordinated and flexible approach to governance, that encourages and allows multi-level action and manages conflicts and inefficiencies. This requires a different type of governance to encourage active participation of end-users and business, align the drivers of these additional actors and to distribute benefits fairly and efficiently (Dietz, Ostrom, and Stern 2003; Janssen and Ostrom 2006).

This paper combines the findings of existing case study research with insights from theories of multi-level governance, co-evolution and institutional dynamics to develop a framework to analyse how governance systems might need to change to accelerate infrastructure transitions. It uses integrated, service-oriented operation of infrastructure systems as the focus for analysis but generates findings of wider relevance.

In section 2 we describe the approach to and highlights from case study analysis investigating the barriers and enablers of alternative infrastructure operation. In section 3 we discuss the challenges posed by current governance systems to these alternative modes of operation. In section 4 we consider the contribution of three theories of governance relevant to overcoming these challenges. We combine the insights from case studies and from theories of governance in section 5 to develop a framework to improve the understanding of transition to service oriented infrastructure and in particular the role that governance might take in accelerating this transition. Future work is discussed in section 6.

2. Case study analysis

2.1. Case study selection and design

We present here a summary of the methods used to derive insights from case studies; the detailed findings of this analysis will be reported elsewhere. A series of case studies of alternative infrastructure configurations that incorporate service-based practices have been analysed in detail. The analysis aimed to identify the interactions between governance, business, end users and technologies that led to success, the barriers to wider roll-out of the case study and how governance might accelerate the adoption of alternative configurations.

None of the case studies analysed represent full service-oriented multi-utility infrastructure delivery, as defined by this research, in particular, the integration of different infrastructure streams was lacking. However, all displayed some element of the resource-efficient, service-oriented approach fundamental to a MUSCo. Case studies were selected to show a variety of initiators (including local authorities, land owners and community interest companies) to fully explore the challenges that a market-driven regulatory system places on innovative approaches. The case studies are described in Table 1 below.

Table 1: Case study summaries

Case Study	Description (including main technologies)	Location	Utility Sector	Initiator
Woking Borough Council	A Special Purpose Vehicle (including participation of the private sector) designed to save energy in council property and recycle financial savings into low carbon energy generation (via CHP) and retrofit of social housing.	Woking	Energy	Local Authority
Olympic Park Energy Centre	The largest Combined Heat and Power Plant in the UK providing resource efficient heat to the Olympic park and contributing to the Olympic Development Agency's sustainability goals. Now extending heat supply to surrounding developments.	London	Energy	Government Agency
Yorkshire Water Water Saving Trials	Pilot schemes trialling water saving device roll out to provide evidence on water saving potential in response to OFWAT's requirements to provide demand and supply balance and demonstrate action on demand management.	Scarborough and Wakefield	Water	Utility Company
Kimberley Clark Water Recycling Scheme	"Long loop" recycling of effluent from paper mill re-used as process water following intensive treatment. No financial driver for investment (water was previously abstracted from groundwater and discharged to river after settlement). Novel financing mechanism (piggy-backing on a high payback scheme).		Water	Private sector
Eco-Island	Retrofit and low carbon energy schemes on the Isle of Wight. Instigated by Eco-Island Community Interest Company (CIC). Operation of energy generation (small scale wind, CHP and smart grid) will be undertaken by an ESCo run in partnership with the CIC.	Isle of Wight	Predominantly energy	Community Interest Company
Welborne	Proposed development of 3,000 house and employment land. In addition to high levels of sustainability (and updatability), it is proposed that properties and infrastructure will be managed by the community that occupies the site, in a manner similar to a MUSCo.	Portsmouth	Energy, Water, Transport	Landowner

Case studies were analysed using a methodology applying the process of building theory from case study research described by Eisenhardt (Eisenhardt 1989). The process involves a series of stages to collate and analyse case study data:

- Selecting cases – using theoretical, not random, sampling to focus on those that are theoretically useful and constrain extraneous variation.
- Collecting data – using defined protocols and multiple methods to strengthen grounding of theory by triangulation of evidence.
- Analysing data – to identify patterns within and between case studies to force investigators to look beyond initial impressions and see evidence through multiple lenses.
- Shaping hypotheses – by identifying evidence for emerging constructs and looking for replication of logic across cases.

Data collection was undertaken in two stages; firstly, literature related to the case studies was examined and a timeline created for each case study showing the internal and external factors that shaped the evolution of the alternative mode of operation. The observed structure of the agents and assets involved in the alternative mode of operation was mapped and compared with the structure of a mainstream business. The mapping exercise provided a clearer insight into the relationships and interactions that contribute to the emergence of the case study within the mainstream.

Secondly, a series of semi-structured interviews was undertaken to develop an understanding of:

- The evolution of internal and external factors that led to the success of the alternative mode of operation;
- The motivations, enablers and barriers for the development of the alternative models;
- The relationships and interactions of different actors and organisations within the case studies that that contributed to the emergence of the case study within the mainstream; and
- The potential to roll out and upscale the case study or to develop them into service-based utility models.

2.2. Lessons from case studies

Our analysis of the case study outcomes identified a series of barriers and enablers to adoption of resource-efficient, service-oriented infrastructure operation common to the majority of case studies. Our focus in this article is on developing a more theoretical understanding of the process of change and the role of governance in supporting or hindering this change.

Our results highlighted a series of characteristics of successful transitions, which are enumerated below.

<u>Infrastructure governance goes beyond utility governance:</u> The activities in the case studies were initiated by a range of actors, not just utility companies, which are the major focus of current infrastructure governance. The centralised market regulation of the current governance system was found to hinder activities initiated by alternative actors.

<u>Multiple participants: a key challenge, but also a key to success:</u> The majority of case studies required the active participation of multiple actors from a range of sectors. For example, the Eco-Island project required action from international industrial organisations, local businesses, the local

community and the local authority. When end-users are engaged as a key driver and are central to the goal of the project it is more likely to have successful outcomes.

Integration of diverse actors: One of the biggest challenges that case studies faced was aligning the interests of the diverse actors. Once initial interests were aligned a key aspect of success was ensuring that actors derived benefit from participation.

Multi-dimensional relationships, multi-dimensional solutions: The relationships between these actors are multi-dimensional, and it is the combination of these relationships that supports transition. It is important that these relationships do not have contradictory goals. For example, regulators require water companies to demonstrate activities to encourage demand management but do not allow them to generate revenue from activities other than selling water, reducing profits and disincentivising demand management.

Relationships are dynamic: the roles of actors and the relationships between them are not static and evolved as case studies developed and responded to external pressures. For example, the community interest company (CIC) at the heart of the Eco-Island development was fundamental in describing the future scenarios of the island's infrastructure at the early stages of the project. However, as the project nears the implementation stages, detailed technical specification is being devolved to an ESCo, and the CIC will take on the role of the client.

The importance of internal governance: All case studies needed some form of agreement or rules and ways of working to maintain alignment of interests and ensure that benefits were fairly distributed. We term these rules and ways of working, and the organisations or actors needed to implement and monitor them the internal governance of the case study. These internal institutions need to evolve as relationships and drivers evolve.

Systemic approach to technology change: Committing to technological change altered actor motivations and relationships, and vice versa, changing actor relationships altered the way technology was chosen and used. The case studies deployed a range of technologies including; end-use, distribution and supply technologies. However, these technologies were were predominantly developed in parallel to the current infrastructure system. Wider roll out of alternative will need to consider better integration of current and alternative systems.

The case studies show very different characteristics to the mainstream model of infrastructure operation. The cases have evolved and survive at a small scale, which does not disrupt the mainstream and is able to circumvent any barriers presented by the current governance system. It is not clear to what extent these barriers would constrain wider roll out.

3. The current infrastructure governance system

In this section we discuss the extent to which the current governance system is supportive of the proliferation of alternative business models, such as those investigated in the case studies. For clarity we begin with our definition of governance. Governance can be defined in many ways, such as "the use of institutions, structures of authority and even collaboration to allocate resources and coordinate or control activity in society or the economy." (Bell 2002) or "the pursuit of [infrastructure] development for the wider public good" (Smith 2009). Some prefer to consider governance as a system of institutions, which are "ways of structuring human interactions" (Foxon 2011). We consider governance to be a system of institutions which includes organisations, actors and the rules they develop. It is not limited to the actions of national governments but includes the policy developed and implemented by a complex network of non-state actors at international and sub-national levels (Smith, Stirling, and Berkhout 2005).

There is a case for governance of the infrastructure system over and above that which would be expected into a traditional economic sector. The services that infrastructure provides are essential to social and economic development and delivery of these services can have significant environmental impacts. Governance, usually in the form of regulation and policy intervention, is needed to correct the market and system failures that would arise in a purely privatised utility system and to manage a balance between security, sustainability and affordability. The infrastructure governance system in the UK has evolved in parallel with our physical infrastructure systems and the practices of users of infrastructure services (Foxon 2011). Its principal features, relevant to this article, are presented in Figure 1 and described below.

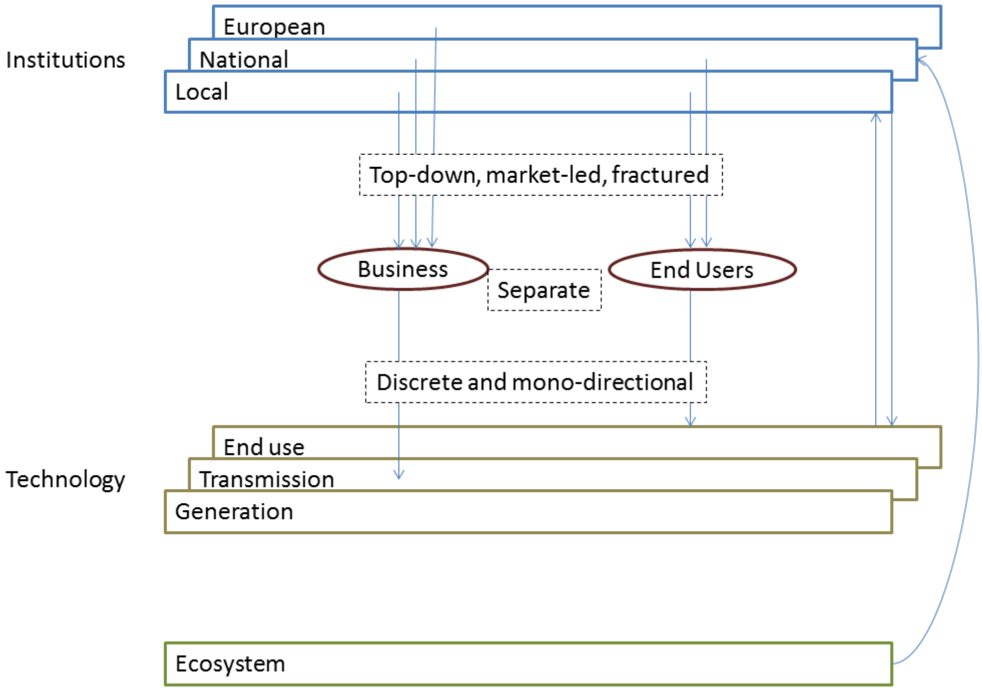

Figure 1: Representation of the current infrastructure governance system. Actors and assets are represented as boxes. The relationships between actors and assets are represented as directional arrows. Particular features of interest are highlighted in dashed boxes.

In the UK, there has been a shift from state controlled infrastructure systems towards liberalisation, private provision and competition (Hall et al 2012). The primary purpose of post-privatisation infrastructure governance was to introduce competition into the infrastructure system, to deliver greater economic efficiency and to protect consumer rights (Mitchell 2010). Despite being a liberalised system, this still represents a very 'top-down' approach to governance and leaves little room for diversity and innovation (CST 2009b).

The current governance system is primarily market-led, which was fit for the purpose of driving cost efficiency and consumer protection but it is unlikely to be appropriate to respond to emerging issues, like climate change (Hall et al. 2012; Mitchell 2010). Responding to these issues will require more investment and more innovative technologies and business models (for example Utility Service Companies). However, these crucial aspects are often under-represented as a result of market imperfections, such as information asymmetries and monopolistic competition (Hall et al. 2012). The market-led regulatory approach can actively constrain more sustainable infrastructure operation. For example, electricity market design and network regulation can 'lock-out' potentially beneficial alternatives, such as development of district energy systems at the urban scale (Bolton and Foxon 2013).

Privatisation of utility sectors has led to the introduction of new actors responsible for the delivery, regulation and financing of utilities to correct market failures and protect customers. This has created a complex and fragmented governance structure (CST 2009a). The profusion of actors can result in duplication of regulation or conflict between regulators. For example the long-term Water Resources Management Plans produced and signed off by the Secretary of State for the Environment were not reviewed by OFWAT who instead had a separate requirement for supply and demand balance planning (Defra 2011). Further complexity is added by the range of scales at which these issues are governed. Regulators can act at local, national or European level, often showing little consistency between scales.

Utility companies (for example, HM Government 2012), technology providers (for example, HM Government 2007) and end users (for example, DECC 2012) are governed separately and their agency in the operation and transition of the infrastructure system is confined to limited parts of the system. End users are perceived as passive receivers of information or managers of their own demand (Shove & Walker 2010). Businesses, other than traditional utility companies, tend to be marginalised, which excludes the significant contribution of alternative providers, such as technology companies and local authorities. There is little consideration of their interaction or the potential for there to be positive interaction, contributing to transition.

These actors are conceived to interact with the physical infrastructure system (or technologies) at discrete and different levels. End-users interaction with technology is limited to end-use technologies, and their behaviour is seen to be independent of this technology. Businesses may interact with either generation or transmission technologies, which are regulated separately.

Some infrastructure systems (for example water and energy) are regarded as private goods, which has driven the market-led approach to infrastructure governance. However, most infrastructure systems actually display characteristics of public and common goods (Frischmann 2005). When you consider the services that infrastructure provides (comfort, cleanliness, mobility) these could be considered to be non-excludable; all citizens should have access to these services and, therefore should not be excluded from use. This is reflected, to some extent in the limitations placed on infrastructure providers cutting customers off, for example the Water Industries Act 1999 prevent water companies from disconnecting domestic customers for non-payment of bills (HM Government 1999). There is extensive evidence that non-market and non-state actors can successfully manage natural resources, which are public and common goods (Janssen and Ostrom 2006). This indicates that alternatives to market-led governance could be effective and that there is a significant role for non-market actors in infrastructure delivery and governance.

4. Insights from governance or transition theories

The current infrastructure governance system is limited in its ability to support the the acceleration of adoption of alternative, sustainable, modes of infrastructure operation. New governance arrangements are beginning to be developed cautiously and slowly but the scale of change necessary to delivery sustainable, secure and affordable infrastructure requires change at a much faster rate. A new approach to governance is needed that will remove barriers to the transition of infrastructure operation from supply of unmanaged demand towards resource-efficient service delivery. Governance must create the right pressure for change and support the resourcing and co-ordination of the response to this pressure (Smith, Stirling, and Berkhout 2005).

Below we elaborate on the contribution of a series of theories to understanding how governance might better support the system change represented in the case studies.

4.1. Multi-level governance

A key factor of success in case studies was the presence of multiple actors whose goals were aligned, where there was a strong network and who had shared commitments. This is not supported by the current top-down and fractured approach to governance and alternative approaches are needed.

The study of multi-level governance is concerned with the changing interaction between different levels of governance and the engagement of non-governmental actors in policy development and delivery (Smith 2007). There is agreement that this dispersal is more efficient and that it is desirable for governance to be multi-level to capture variations in territorial reach of policy and to better reflect diverse preferences among citizens (Marks and Hooghe 2003). The distribution of responsibility promoted by multi-level governance is very relevant to our research area, where change can be initiated by different actors, at different scales and is likely to involve more than one actor.

There are contrasting views of the ideal form of multi-level governance in the literature which Marks and Hooghe (2003) have formalised in two types:

Type 1 – well ordered, nested responsibilities at clearly demarcated levels, usually following territorial boundaries. Responsibilities are distributed between multi-functional institutions and networks. However, whilst clear demarcation of responsibility is beneficial, it can be undermined by a breakdown between levels as a result of the varying drivers and capabilities of actors at different levels (Leventon and Antypas 2012). Type 1 multi-level governance tends to provide a greater degree of stability and security in policy direction but has been criticised for lacking innovation and adaptation to changing conditions (Smith 2007).

Type 2 – more fluid and problem focussed, intended to be flexible, rather than durable, with intersecting membership. Presents more opportunity for innovation and adaptation. There are some examples of type 2 multi-level governance in the UK, particularly in the former Regional Development Agencies (Smith 2007). However, it presents significant challenges in communication and monitoring progress, can reduce the stability of the policy environment and reduces certainty about future policy and represents a significant change from the current top-down approach.

Type 2 would seem to be more suited to the purpose of delivering the multi-actor approaches we found in the case studies. The problem-focussed nature of this form of multi-level governance supports engagement of a multitude of actors across territorial scales and encourages more integrated and innovative policy (Smith 2007). A type 2 approach identifies three constituent governance processes: establishing common problem framing; building resourceful actor networks; and negotiating commitment between different interests (Keeley and Scoones, 2003). These processes would support the alignment of interests, which is challenging in multi-actor activities.

One challenge of effective operationalisation of multi-level governance is that Type 2 tends to be embedded in legal frameworks determined by Type 1 (Marks and Hooghe, 2003) and ultimately depend of Type 1 authority for their effectiveness (Smith 2007). This is a particular problem in the governance of infrastructure, where the strategic regulation of infrastructure and markets are negotiated at the national government level. Sub-national and non-governmental actors have very little direct control over these issues. This can actively inhibit the adoption of decentralised solutions that arise from actors outside the traditional infrastructure marketplace (Bolton and Foxon 2013; Smith 2007).

Multi level governance provides us with some useful lessons to take forward to our framework:

- The importance of developing a common framing of the problem, which requires translation between different discourses and actors (Smith and Stirling 2006).
- The need to engage private, public and civil society partners in the process of innovation, business development, community involvement, knowledge production, infrastructure provision, communication, regulation, market creation and policy (Smith 2007).
- The need for national regulation to allow innovation at different scales and from different, non-utility company actors (Bolton and Foxon 2013).

However, there are a number of limitations to the application of multi-level governance in isolation to understanding how governance might better support the system change represented in the case studies. Multi-level governance is somewhat passive in its approach to analysis, in that it aims to analyse the characteristics of relationships, rather than understand how these relationships will evolve and how this can be used to drive change. Furthermore it does not specifically address the interaction of actors and technology, which is fundamental to infrastructure transition (Foxon 2011). Nor does it adequately deal with the nature or structure of internal governance of partnerships, thus we look for additional theories that might explain these phenomena.

4.2. Coevolution

The evolution of relationships and causal interactions between actors and the technology system are captured in Foxon's coevolutionary framework, which defines five coevolving systems necessary to understand industrial and economic change (Foxon 2011):

Ecological systems can be defined as systems of natural flows and interactions that maintain and enhance living systems.

Technological systems can be defined as systems of methods and designs for transforming matter, energy and information from one state to another in pursuit of a goal or goals.

Systems of institutions are defined in the framework as ways of structuring human interactions. This is taken to include, for example, regulatory frameworks, property rights and standard modes of business organisation.

Business strategies can be defined as the means and processes by which firms organise their activities so as to fulfil their socio-economic purposes.

User practices may be defined as routinised, culturally embedded patterns of behaviour relating to fulfilling human needs and wants.

Each system evolves under its own dynamics but this evolution affects the dynamics of one or more of the other systems. One element of the framework of great relevance to our case study findings is the observation that coevolution can lead to the development of joint structures between different systems (which are analogous to our multi-actor initiatives; for example, the community interest company in Eco-Island or Special Purpose Vehicle in Woking). These joint structures may remain stable, and contribute to a long-lasting transition, or might be disrupted by change at the micro or macro level, as well as internal dynamics. Governance has a role to play not just in supporting the creation of these joint structure but in minimising disruption at the macro-level (for example by removing market regulation barriers to district heating systems) to support the longevity of joint structures.

The framework has particular application to the analysis of the interaction between social and technological elements within potential transitions of infrastructure systems. Focusing on identification of causal interactions improves our understanding of the processes by which systemic change occurs. It allows us to see how technological change can change actor motivations and relationships, and vice versa, changing actor relationships can alter the way technology is chosen and used. This is particularly significant in relation to the observation that current actors interact individually and with discrete parts of the technology, which often reduces total system efficiency. When actors combine into joint structure there is a greater potential for them to interact with an infrastructure system in a more integrated and effective manner (for example, selecting more complementary supply and end-use technologies to reduce the need for storage).

The coevolutionary framework gives greater insight into how decisions made by policy makers and other actors could accelerate systemic change by promoting beneficial causal interactions, improving the stability of joint structures and supporting more systemic innovation and deployment of technologies. However, it does not go far enough to describe how internal rules could improve the stability of joint structure.

4.3. Institutional Dynamics

The more complex partnerships and differing actors motivations within the joint structures mean that some system of internal governance is required, which sets out the roles and responsibilities of different actors. Elinor Ostrom's work on institutional diversity has provided a great deal of insight into the diverse arrangements that make it possible to conserve and efficiently utilise jointly managed resources. This work has focussed on collective management of social-ecological systems (SES); however, these systems have much in common with infrastructure systems, particularly those which demonstrate characteristics of common and public goods. We discuss in this section the potential for the application of Ostrom's work on self-governance of natural resources to infrastructure systems.

Ostrom identifies a series of variables that are suggested to affect the likelihood of resource users to self-organise to manage a particular SES (Ostrom 2009). The capacity to create effective governance of SES depends on the nature of these variables; particularly how they affect the costs of investing in better norms and rules and the benefits of self-organising. The variables relate to the nature of the resource system, the characteristics of the resource users, and the capacity of resource users, in terms of their autonomy and system knowledge. These variables were developed into design principles to help understand the requirements of internal systems of institutions required to support self-governance (Ostrom 1990). These principles were updated by Michael Cox, Gwen

Arnold, and Sergio Villamayor-Tomas and reported in Ostrom (2009). They represent "*core factors that affect the probability of long term survival of any institution developed by users of a resource".* The updated design principles are provided in Table 2 along with a brief description of how they might be applied to infrastructure.

Table 2 - Design principles for collaborative management of resources and application to infrastructure

Design principle	**Application to infrastructure**
1A. *User Boundaries*: Clear and locally understood boundaries between legitimate users and nonusers are present.	User boundaries may be less relevant to some infrastructure systems and strict delineation could result in duplication of technologies and networks. It might be more relevant to understand interconnection with other parts of infrastructure system.
1B. *Resource Boundaries*: Clear boundaries that separate a specific common-pool resource from a larger social-ecological system are present.	
2A. *Congruence with Local Conditions*: Appropriation and provision rules are congruent with local social and environmental conditions.	The infrastructure system and service provided is congruent with the existing socio-technical system and needs of the end-users.
2B. *Appropriation and Provision*: Appropriation rules are congruent with provision rules; the distribution of costs is proportional to the distribution of benefits.	Agreements are in place for service provided to end-users, costs of service and arrangements for maintenance and renewal.
3. *Collective Choice Arrangements*: Most individuals affected by a resource regime are authorized to participate in making and modifying its rules	Actors are able to participate in decisions on charging, maintenance and renewal of infrastructure.
4A. *Monitoring Users*: Individuals who are accountable to or are the users monitor the appropriation and provision levels of the users	End-users or organisation reporting to end-users monitor end-use to ensure agreed levels of service are delivered but not exceeded.
4B. *Monitoring the Resource*: Individuals who are accountable to or are the users monitor the condition of the resource.	End-users or organisation reporting to end-users should maintain and update technology to ensure it is the most efficient.
5. *Graduated Sanctions*: Sanctions for rule violations start very low but become stronger if a user repeatedly violates a rule.	Rules are in place in the event that service agreements are breached or maintenance is not implemented.
6. *Conflict Resolution Mechanisms*: Rapid, low cost, local arenas exist for resolving conflicts among users or with officials.	Mechanisms are in place to maintain alignment of motivations of different actors.
7. *Minimal Recognition of Rights*: The rights of local users to make their own rules are recognized by the government.	Governance of wider infrastructure system needs to enable joint structure activities.
8. *Nested Enterprises*: When a common-pool resource is closely connected to a larger social-ecological system, governance activities are organized in multiple nested layers.	The connection between governance of local system and rules for governance of wider infrastructure systems is recognised and articulated.

Both the variables affecting the likelihood of self organisation and the design principles for supporting institutional survival have a high degree of relevance to infrastructure. These design principles could be further developed to support the design of internal institutional arrangements for infrastructure operation. They would support the stability of joint structures and increase their resilience to external influences. This could also help to guide the structure of external governance to ensure that disruptions are minimised.

5. Analysing the contribution of governance to infrastructure transitions: a conceptual framework.

We outline in this section a governance analysis framework that has been developed to improve the understanding of transition to resource-efficient, service-oriented infrastructure and in particular the role that governance might take in accelerating this transition. The framework organises important elements and relationships identified in our analysis of existing theories and in our empirical research to help analysts examine a diversity of situations. It also provides a "*metatheorectical language to discuss emerging theories of particular parts of the framework*" (Ostrom 2009).

It allows analysts to identify elements or relationships that are absent from a system of interest or that are constrained by the current governance system. From this, alternative approaches to governance can be identified that remove barriers to transitions or enable the creation of a necessary element and accelerate desirable transitions. This governance analysis framework has been developed to promote a particular transition, to service oriented infrastructure, but it is relevant to other transitions. The framework is presented in figure 2 and described in more detail below.

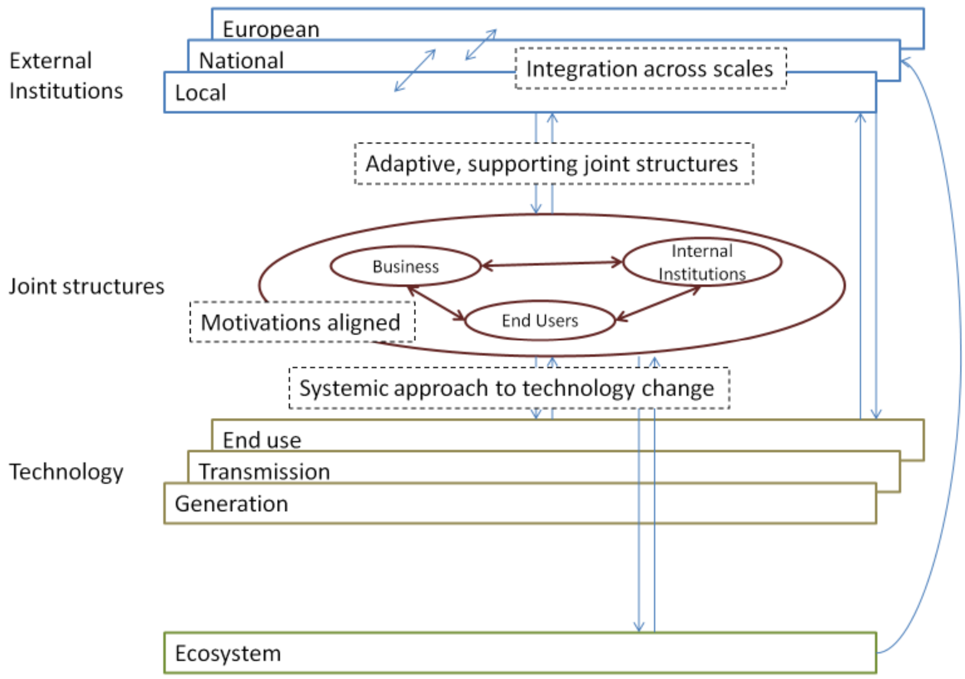

Figure 2: Governance analysis framework

The key elements of the system (the institutions, technology and ecosystem) are analogous to those used to describe the current infrastructure governance system in figure 1. However, the relationships between different parts of the system are substantially different. We describe these relationships below.

Business and end-users are no longer separate but combine to form joint structures. The creation and evolution a joint structure of business, end users and often governmental organisations was a key factor of success identified in case study analysis. These joint structures align the interests and motivations of the heterogeneous actors, whilst still delivering benefits to all participants.

The scope and role of actors has broadened, including businesses and end users. Many different types of businesses participate in the transition, including technology providers, data management specialist and property developers, as well as the traditional locus of utility companies and this needs to be recognised by external institutions. End users become active participants in infrastructure system transition.

The joint structures have internal institutions to set the rules of interaction and to make them more robust to change. These internal institutions maintain alignment of motivations and fair distribution of benefits and could be developed following Ostrom's design principles for self-organising systems.

External institutions are more integrated and adaptive. The formation of joint structures is encouraged and enabled by institutions at all levels. The description of these institutions a 'external' implies a division between internal and external actors. In reality the same organisation could operate in both systems; for example, DECC could partner with a private sector organisation in a scheme, which would have to operate under the policy set by DECC.

The relationships between external institutions and joint structures are reciprocal (rather than top-down) and dynamic to allow coevolution of governance and joint structure operation. These relationships support the internal institutions of the joint structure by allowing them to, for example generate revenue and interact with other joint structures unimpeded. A significant challenge for external institutions is that the form and scale of joint structures will vary significantly.

Interaction between technology and actors users is more systemic and coevolving. This is moderated by the joint structures who promote interaction with the infrastructure system in a more integrated and effective manner (for example, selecting more complementary supply and end-use technologies to reduce the need for storage).

The ecosystem plays a more central role in motivating change within the joint structure or external institutions and it is recognised that its state will be changed by the actions of the joint structure.

Finally, the relationships between different part of the system will co-evolve and both internal and external governance will need to adapt to this co-evolving system, whilst maintaining the focus on sustainability.

6. Discussion

This paper responds to the need for a radically different approach to the governance of infrastructure to accelerate a transition to a more sustainable infrastructure system. Case study analysis has identified a number of characteristics common to successful transitions towards more resource-efficient, service-oriented infrastructure operation. These alternative modes of operation are initiated by actors outside the traditional locus of utility companies and the majority require active participation of multiple actors from a range of sectors. The alignment of motivations and distribution of benefits amongst these diverse actors is one of the key challenges of these alternative modes of operation. The relationships between actors are multi-dimensional, dynamic and need to be moderated by some form of agreement or rules to maintain alignment of interests and fair distribution of benefits. Actors tended to have a closer relationship with technology systems and interact with multiple parts of the infrastructure system.

These characteristics are substantially different to the infrastructure system conceived by the current governance system. Alternative modes of operation are able to exist within the confines of the current, unsupportive system only because they are small enough in number that they do not disrupt the mainstream system. A fundamental change in governance would be required to accelerate the adoption of alternative models to an extent to which they represent a transition from the mainstream.

We use these characteristics and insights from multi-level governance, coevolution and institutional dynamics to develop a better understanding of how the current governance system would need to change to encourage the transition to a more sustainable infrastructure system (which we define as being more resource efficient and service oriented). This is articulated as a governance analysis framework, which organises actors, technology and their relationships to help analysts to examine a diversity of situations. The purpose of the framework is to support the identification of alternative approaches to governance that could accelerate desirable transitions.

The governance analysis framework creates a new joint structure, where our multi-actor partnerships can congregate and create internal institutions to support the alignment of motivations and distribution of benefits. These joint structures are supported by more integrated, innovative external governance, which adapts to the evolving nature of the joint structure. The interaction of these joint structures with technology creates a point of integration across multiple scales and multiple parts of the technology system. A key challenge for governance will be the fact that these join structures themselves will occur at multiple levels and be initiated by a range of different actors.

The governance analysis framework has been developed to promote a particular transition, to service oriented infrastructure, but is relevant to other transitions. It has been developed as a result of a limited number of case studies but could be tested on additional studies with alternative transition end-points.

There is a great deal of potential to further develop this framework to improve its application to governance of infrastructure transitions:

- Further develop our understanding of the joint structure, and in particular the nature of internal institutions required to support self-governance of infrastructure.
- Undertake modelling of specific parts of the framework to examine the consequences of proposed alternative approaches to infrastructure governance, for example the relationship between joint structures and the technology system.
- Apply the framework to analysis of integration between infrastructure systems (such as water and energy) to identify how governance might support exploitation of cost and resource efficiencies resulting from infrastructure interdependence.

The framework developed in this article represents the first steps towards developing a new approach to infrastructure governance to accelerate the transition to a more resource-efficient, service-oriented infrastructure system. It is hoped that such a framework will ultimately become a key tool in understanding how to achieve transition to a more sustainable infrastructure systems.

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