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Infrastructure decision-making: Opening up governance futures within techno-economic modelling

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Abstract

Techno-economic modelling is an important tool in evidence-building, futures assessment and decision-making in policy for socio-technical systems. However, critical assessment of the fit of sophisticated models into a decision-making context is often hidden or overlooked. Using the case of a national infrastructure systems model, this paper connects conceptions of infrastructure governance to techno-economic modelling assessing future infrastructure performance. Analysis of modelling input to a UK national level infrastructure policy process demonstrates the importance of governance understanding within infrastructure modelling for policy and it highlights the risks of not explicitly considering governance assumptions. Going on to pursue a more integrated approach to infrastructure modelling and governance, socio-technical researchers embedded within a model development research project are able to observe model development, analyse an early policy application, and facilitate discussions and co-development work with modellers. A methodological framework, building on recent transitions research 'bridging' socio-technical and techno-economic approaches, for connecting infrastructure governance understanding into techno-economic modelling analyses is presented and its use within this UK infrastructure modelling project is discussed. The integrated approach taken and the methodological framework developed are potential tools for researchers working with techno-economic models to support policy decisions; they show potential for further research on infrastructure futures.

Keywords: infrastructure, governance, policy decisions, techno-economic modelling, socio-technical systems

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1 Introduction

Modelling has an important role to play in evidence and decision-making for changing socio-technical systems. It is a powerful tool both for envisioning the future and for informing decisions that shape policy, practices and systems. Therefore, to make steps towards sustainability transitions, particularly in high-inertia systems such as infrastructure, modelling can be a key process within policy decision-making and potentially an important site to access representation of transitions understanding. However, important models are often techno-economic in character and, by nature, focused on elements that are quantifiable. Where techno-economic modelling is used, for example to provide a system overview for decision-making, this can have many benefits. However, a key challenge is how to connect socio-technical and transitions understanding with techno-economic approaches to modelling and into policy and system decision-making. To make the most of this potential, understanding of how models fit with structures and processes of decision-making needs to be considered alongside model development and/or application. Using the concept of governance to refer to the structures and processes that define decisions and shape decision-making (e.g. Goldthau, 2014), this paper reports on research investigating connections between a techno-economic model to support decision-making in UK infrastructure development and conceptions of infrastructure governance. Drawing on transitions research that has sought to combine qualitative and quantitative approaches, a framework is developed to support the integration of socio-technical understanding of change and transformation into the use of modelling for policy/investment decisions in infrastructure.

Considering the needs for society to adapt in the face of the uncertainty and complexity of the COVID-19 pandemic, Saltelli et al., (2020) present a reminder of the dangers and difficulties in the development and interpretation of modelling that accompany its promise in supporting decision-making. In particular, it is easy for assumptions (carefully made in model development) to become hidden in the use of modelling outputs; for model development aims and model application to become misaligned; and for uncertainties to become misrepresented. Further, models cannot fully reflect real-world decision-making, many do not include multiple decision-makers and they exclude politics, political economy and the role of institutions. Recent research in the transitions and energy fields has looked to address some of these challenges by developing ways to combine qualitative, socio-technical approaches with numerical modelling processes. This has included pursuing socio-technical models (e.g. Li & Strachan, 2017) and new processes of combining different types of evidence with the dominant techno-economic modelling (e.g. Hiteva et al., 2018; Nilsson et al., 2020) as well as developing socio-technical scenarios of transitions (e.g. Foxon, 2013; McDowall, 2014; Trutnevyte et al., 2014; Turnheim et al., 2015; Geels et al., 2020; Hof et al., 2020; Köhler et al., 2020; Nilsson et al., 2020). This paper draws on these developments, that are predominantly focused on energy systems and on transitions to sustainability. It develops a framework to enable critical consideration of socio-technical understandings and prospects of system transformation in infrastructure planning and investment decisions.

Important factors in considering the use of models in making policy decisions for infrastructure are 1) incumbency of/norms for large techno-economic models in national policy-making (e.g. Hiteva et al., 2018; Nilsson et al., 2020); and 2) challenges of working with, responding to, and dealing critically with some of the assumptions about the relationships between social and technical elements embedded in such models (Hiteva et al., 2018; Nilsson et al., 2020; Saltelli et al., 2020). For example, assumptions are made that smart meters can be rolled out in a linear way across the country or that people make rational decisions about how much energy they use. In response to these conditions, this research takes an approach of engaging socio-technical thinking with model development for a large techno-economic model.

Infrastructure sectors, understood as the socio-technical systems providing fundamental services such as mobility, warmth and communication, underpin the economic, social and environmental functioning of societies. Development and change in infrastructure systems is an important factor within transitions to sustainability (Loorbach et al., 2010; Markard, 2011; Roelich et al., 2015). However, decisions for infrastructure change, and the governance processes supporting them, are neither situated within nor fully aligned with decision-making for transitions. Investment and planning decisions often prioritise economic or connectivity factors, and can have long-lasting impacts on patterns of travel and energy demand. A transition to sustainability, including meeting emissions targets like Net Zero, may demand more radical changes to infrastructure systems. Better understanding of infrastructure development and governance are needed to facilitate infrastructure change as part of transitions for sustainability. Defining governance as "the institutions, mechanisms and processes through which economic, political and administrative authority is exercised" (Goldthau, 2014 p135), the governance of infrastructure needs to be able to change to enable the broader range of infrastructure futures needed for transition. Openness to new modes of infrastructure governance is part of enabling these changes. Therefore, changing governance, in terms of adaptations in priorities and in investment and development processes, needs to be accommodated in modelling of infrastructure performance over long time periods.

In the UK policy context infrastructure development needs to contribute to reaching the new target for Net Zero emissions by 2050 (BEIS, 2019b); it is also adapting to a more strategic and co-ordinated approach to infrastructure investment, in particular through the creation of the National Infrastructure Commission (NIC) (HM Treasury, 2017) and inclusion in the Industrial Strategy (BEIS, 2017). These developments have created more demand for data, insights and tools to support decision-making for infrastructure. This setting for infrastructure policy decisions demands development of both environmental and economic performance of infrastructure and, further, the incorporation of combined performance and interdependencies between traditionally separate infrastructure systems. The development and application of the National Infrastructure Systems Model (NISMOD) fits into this context; it is an ambitious techno-economic model that applies a system of systems approach to assessment of UK infrastructure (Hall et al., 2016).

However, particularly with the timescales involved and degrees of change needed in infrastructure development, there is a pressing need to incorporate critical thinking on the assumptions about governance & innovation for future infrastructure. Lack of acknowledgement of the potential influence of governance changes on system development and performance within these sectors results in a gap in 1) understanding; and 2) approaches to examine potential influences of governance on the redirection of system development. The research reported here features a small team of socio-technical systems researchers working alongside a large team of engineering and economics researchers focused on model development for NISMOD 2.0. A methodological framework and a series of co-development activities have been developed linking understanding of governance to techno-economic modelling analysis of infrastructure. This research aims to facilitate the consideration of infrastructure futures drawing on socio-technical approaches alongside techno-economic modelling. Through the engagement with the modelling process, the research encourages further development of critical thinking over the representation of governance futures in model analysis and development. The framework developed and presented here can provide a starting point for future research seeking to integrate potential changes in governance with the development and application of techno-economic models. Further, the application of this approach indicates that different model structures may sometimes be needed to capture different governance arrangements.

The paper comprises five further sections. Section 2 introduces NISMOD and presents a governance analysis of an important application of NISMOD 1.0 in a UK national level policy process. This highlights governance assumptions embedded in the model and demonstrates the need to be able to check and adjust governance assumptions within analysis. Insights from energy and transitions research using ‘bridging’ (McDowell, 2014; Turnheim et al., 2015; Nilsson et al., 2020) to combine qualitative and quantitative approaches, underpin the methodological framework developed to guide interactions between modelling actors and governance understanding. This is introduced in section 3. Section 4 describes the application and testing of the framework with a range of activities to develop points of connection between governance thinking and the development and use of the NISMOD model. The discussion, section 5, reviews these three elements of the research and reflects upon findings for socio-technical approaches in policy decision-making as well as incorporating governance analysis into consideration of infrastructure futures. Section 6 concludes.

2 Governance & techno-economic modelling: understanding opportunities for connection

This section explores the potential implications of different approaches to infrastructure governance, within a case study of infrastructure planning in the UK. It focuses on the use of the National Infrastructure Model (or NISMOD) to generate quantitative representations of infrastructure change in the UK between 2015 and 2050. This modelling was carried out for the National Needs Assessment (NNA), which was led by the Institute of Civil Engineers (ICE)[2]. The Assessment was designed to create a vision for future infrastructure development to meet a range of long-term policy goals.

The analysis presented in this section considers the implicit governance assumptions that are embedded in the model runs for the NNA, and highlights governance changes that might be required for the patterns of investment within those model runs to be implemented in practice. The policy report (ICE, 2016), internal project documentation on the modelling and discussions with NISMOD modellers provided the sources for the analysis. This analysis highlights the importance of changes in governance within long-term infrastructure transitions that cover multi-decadal timescales. The experience and understanding gained through this analysis provided the foundations for the integrated approach to governance and techno-economic modelling that is presented in later sections of this paper.

2.1 The case of NISMOD

NISMOD is a system of systems modelling platform and database for UK infrastructure. It is composed of five sector specific models covering energy, water, transportation, solid waste and ICT that can be run separately or interdependently. The sector models are set up to produce comparable metrics, use common contextual inputs (e.g. population change data), and to interact across key known infrastructure interdependencies. NISMOD 1.0 (used in the assessment analysed below) focused at the national level whereas the development of NISMOD 2.0 (under development by the ITRC-MISTRAL project) also includes analysis of local infrastructure performance.

The sector models contained within NISMOD include a representation of the physical system and can assess performance under a range of conditions. The infrastructure systems represented within the model have different architectures. This is both in terms of the structures and arrangement of physical/operational elements and in the connected structures and processes around decision-making. Further, in examining long timescales (upwards of 15 years) an important aspect of these analyses of potential system performance is system change; this includes changes in conditions (e.g. population and demand changes) but, crucially, also the potential developments to meet demand and improve performance. To incorporate infrastructure development in the analysis sector-focused 'strategies' are included. These strategies capture patterns of infrastructure investment through a defined list of projects and decision-making algorithms. In the NNA the strategies developed draw on the visioning work of the Executing Group (see below). The sets of strategies applied for the energy, transport and water sectors within the NNA exercise form the basis of this governance analysis of the application of NISMOD. A subset of the five sectors in the model was chosen for simplicity, focussing on these three national and established sectors.

[2]The creation of the National Infrastructure Commission (NIC) was announced as the NNA was getting started. Sir John Armitt initiated the NIC, and went on to be a member of the NIC and became the permanent chair in 2018 (HM Treasury, 2018). He had already led the Armitt review that had a role in the creation of the National Infrastructure Commission. The NNA can be seen as a precursor to the National Infrastructure Assessment (NIA),conducted every 5 years by the NIC. The first NIA was produced in 2018.

2.2 Governance analysis of the application of NISMOD 1.0 in the NNA

The ICE's NNA was overseen by its Executive Group that was composed of industry experts from the relevant infrastructure sectors (a full list of the organisations represented is included in the NNA report (ICE, 2016)). Overseen by the Executive Group but incorporating workshops with a wider sample of industry representatives and consultation stages, a process was followed that included:

1. a vision for infrastructure, developed by the Executive Group
2. future needs for UK infrastructure, taking into account likely developments; and
3. a list of projects, with information on potential performance, costs and timing.

NISMOD 1.0 was used to quantify future demand for infrastructure services including the effects of expected efficiency improvements and/or interventions to reduce demand. For each sector, the modelling considered the type, size and timing of investments required to meet future demand. Within the analysis these investments were grouped and applied through sets of sector strategies (outlined for the energy, transport and water modelling in tables 1-3, below). Where sector strategies match particular interventions or projects with investment, an important starting point for the list of candidate projects to be inserted into the analysis was the National Infrastructure Pipeline (HM Treasury & IPA, 2016). When it was published by HM Treasury and the Infrastructure and Projects Authority (IPA), it was said to be "a comprehensive forward-looking assessment of the planned investment in UK economic infrastructure across both the public and private sectors" to 2021 (HM Treasury & IPA, 2016). For the NNA analysis to 2050, the extension of the investments (and outline interventions/projects they purchased) from 2021 to 2050 relied on expert views. The NISMOD model was used to choose the least cost set of investments to meet demand and fit within other constraints (such as emissions requirements, set by analysts within different modelling scenarios).

The sets of strategies that were used to model the energy, transportation and water sectors are summarised in Tables 1-3 below. Apart from the inclusion of a 'no intervention' strategy, each set of strategies is structured differently to reflect the different policy priorities for each sector.

Table 1 Energy sector strategies in the NNA modelling

Strategies	Description
Unconstrained Demand	Growth in energy demand follows current trends; with minimal uptake in energy efficiency, conservation and fuel switching.
Unconstrained Demand + Electrification	Additionally features the electrification of heat and transport.
Demand Management	Adds implementation of technological and behavioural measures such as energy efficiency, fuel switching, local heat networks, electricity storage and demand response and reduction to reduce demand on gas and electricity networks. This strategy also includes electrification of heat and transport.

Table 2 Transport sector strategies in the NNA modelling

Strategies	Description	
No build	Where transport demand is left to increase in accordance with historic trends and no new capacity is built to accommodate this rise.	
Systems efficiencies to maximise the use of existing infrastructures	Ambitious systems efficiencies are pursued through the adoption and integration of sophisticated digital technologies.	NIP - road and rail schemes detailed in the 2015 NIP. These schemes are specified up to 2022.
		NIP+ - includes the NIP strategy investments and further investments (at the same level as the NIP) between 2022 and 2050. Further investments are targeted to reduce congestion.

		NIP++ - includes the NIP strategy investments up to 2022 and further investments to 2050 that are double the level of the NIP. These investments are also designed to reduce congestion.

Table 3 Water sector strategies in the NNA modelling

Strategies	Description
4 demand strategies	Unconstrained demand, only leakage reduction, only demand reduction, and leakage plus demand reduction.
Supply Strategy 1: local	Prioritises water demand being met through local solutions "such as reservoirs, desalination, new groundwater and effluent reuse".
Supply Strategy 2: resource driven	Favours using locations with greater water resources to respond to capacity shortages elsewhere – this involves building additional reservoir capacity in the west and north, and using inter-company water transfers to meet shortages in the southeast.
Wastewater: 3 strategies based on demand	The strategies tested in the wastewater modelling are based on different levels of water demand (per capita water use – litres/person/day): unconstrained demand (150 l/p/d), medium demand reduction (127 l/p/d) and high demand reduction (117 l/p/d).

The NNA did not consider the current or future governance of infrastructure sectors in any detail. For the futures modelled using NISMOD to be possible, decisions would need to be made by a range of actors including governments, firms and households. Furthermore, some of these futures would require significant changes to the way in which infrastructure sectors are governed, including the policy frameworks and instruments that are implemented.

The analysis in this paper addresses this shortcoming by considering 1) what assumptions about governance are implicit in the strategies that were modelled; and 2) what governance changes might be required for the implied patterns of decision-making to occur.

Table 4 summarises the results of this analysis for the energy, transport and water sectors. It shows the primary policy goals that are embedded in the NNA strategies (although some are designed to meet more than one goal), how changes are represented in the model, and some potential governance implications of the model results.

Although the primary emphasis of the analysis is at the national level, it is likely that local and regional changes to infrastructure governance would also be required for some of the strategies explored for the NNA. This is particularly the case for the transport sector.

Table 4 presents differences, across the three sectors, both in the treatment of system changes and in the policy priorities featured in the strategies and analysis for the NNA modelling. These differences highlight some of the complexity present in decisions to be taken across national sectoral systems – where differences in priorities and conceptualisations of change will need to be reconciled. Therefore, examining the model results from the point of view of governance highlights the need for governance changes in order to bring about changes in technology and practices.

Table 4 Summary of Governance analysis of the NNA

	Energy	Transport	Water
Primary policy goals embedded in strategies	Reducing emissions	Alleviating congestion	Sufficient supply of services
Representation of change in model	A relatively wide range of futures including continuation of current trends; electrification of transport and heat; and a more radical future focusing on demand management	Implementation of projects to increase capacity. The list of projects is based upon the NIP pipeline. Increases in system efficiency are also included	New extraction opportunities, new transfer links, different water supply plants (such as desalination), reducing demand and leakage
Governance implications of priorities/choices	Mix of electricity and heat technologies may require different governance arrangements and policies (e.g. for centralised vs decentralised approaches); balance of emphasis between investment in supply, networks and demand could also require changes to governance.	Different governance arrangements and policy priorities prevalent at different scales; whether decisions being taken locally or nationally is likely to effect the projects proposed and selected. System efficiency may require new approaches – for example governance changes needed to incentivise shift to electric vehicles	Different governance arrangements required for national supply system (making the most of water resources) vs local systems that could mean simpler control and transport requirements
Examples/illustrations	1) Large scale technologies such as carbon capture and storage or nuclear require different policy instruments and financing than distributed power generation; 2) Greater emphasis on demand management implies fundamental changes to market rules, business models and policy priorities.	Urban public transport authorities are often set up across the various transport sectors and can have accountability to local voters and urban policy interests (e.g. air quality). Whereas national governance arrangements are focused around technology-defined and regulated networks (e.g. railways)	Water transfer arrangements require not only appropriate water transportation infrastructure, but also appropriate contractual arrangements need to be made and enforced.

Energy

In the analysis of the energy sector different supply technologies are considered that would require very different governance arrangements both for implementing and operating facilities. Large scale, high-cost power generation plants demand different finance, accountability and regulatory structures to distributed, small-scale generation. For heat decarbonisation, the NNA report suggests a mixed strategy. This requires technology and infrastructure changes that vary by location, and presents considerable challenges for current centralised governance and policy arrangements. To implement this strategy is likely to require a set of governance arrangements that can support different technologies and decisions being made in different parts of the country. They would also need to facilitate co-ordination between this variety of approaches and across different scales (e.g. national infrastructure, local/city services & household). Carbon capture and storage (CSS) is also included in the NNA strategies, and is likely to be required to decarbonise power, industry and heating. However, there is no incentive framework in place for large-scale deployment. The need for significant governance changes to introduce CCS is illustrated by the recent consultation on business models for CCS (BEIS, 2019a).

Transport
In the case of transport the modelling strategies rely heavily on the set of projects defined at the national level (the National Infrastructure Pipeline). However, the priorities and processes operating centrally can sometimes be in tension with local governance processes and priorities that are also important in the development of transport systems. For instance, city regions often govern transport across transport modes (e.g. Transport for London) and key issues can involve very local measures such as air quality or affordability.

Further, to achieve the switch to electric vehicles highlighted in the energy strategies, requires charging infrastructure, investment in networks and (possibly) changes in taxation regimes. Transport electrification requires charging points, the development of standards for electric vehicles and incentives to switch. However, potential changes to travel behaviour and business models also need to be considered. Where these changes are combined with vehicle automation there will also be a need for governance processes and measures to ensure safety & security.

Water
The water modelling supply strategies focus on selecting between a national, move-the-water-to-demand approach and prioritising meeting demand within the local catchment. The national approach might be considered the more physical/technological approach. However, water transfers require not only the pipes/transportation necessary but also the means of setting up and enforcing accompanying contractual arrangements; and the availability of physical transfer is likely to influence negotiation over contractual arrangements and vice versa. The more local supply strategy in the NNA that keeps water supply and usage co-located as far as possible, demands transfers of water through time (instead of space) and this also requires governing (what to use and when) being matched to storage facilities. It could also include initiatives to adjust demand patterns.

Cross-sector findings
There are also general lessons from this analysis which cut across all three sectors. First, there is a lack of transparency about some of the assumptions that have been made by within the modelling. This means that it is not clear what the drivers would be for the investments within each strategy, particularly given that such investments are not driven by a single decision-maker in reality. Second, the strategies that have been modelled do not include spatial information, which means that additional analysis is required to explore the relative roles of decisions at national, regional and local levels. The relative importance of these different levels of decisions (and governance) varies between sectors. Third, the sets of strategies in the three sectors not only have different governance priorities, they also interpret system development in different ways. For example, if the representation of change used in the transport model (engineering projects to increase capacity) were applied in the case of water, a different set of interventions would be captured from those currently included in water modelling.

These three findings show the importance of considering system governance alongside techno-economic representations in modelling and assessment of future (and potential) infrastructure performance. They also highlight the challenges (and potential limitations) in governing and investing in these systems within a national, cross-sector scale.

3 Approach: Framework for combining performance modelling and governance in understanding infrastructure futures

These insights from the governance analysis of the NNA point to a need for a more integrated and interactive approach. The methodological framework described in this section was developed within the ITRC-MISTRAL research project. This framework provides a systematic approach to support the development of narratives about governance and their use to derive assumptions and inputs for the NISMOD model. This approach captures both information that can be modelled as well as information that cannot and should facilitate interactions with the model at different levels of authority (i.e. not just national or sector level) to build a more robust analysis of governance change within the analysis of infrastructure futures. This process highlights governance assumptions being made and it can structure reflection to open up alternative pathways of development, and corresponding relevant ranges of performance characteristics included in modelling, to be evaluated.

The approach developed here is part of a growing body of transitions research that has featured renewed efforts to bridge quantitative modelling and qualitative analysis of future transitions – particularly in the energy sector (e.g. Geels et al., 2020; Li & Strachan, 2017; Turnheim et al., 2015; McDowall, 2014; Foxon et al., 2013). This research has explored ways of bringing qualitative and quantitative thinking together through 1) developments in modelling capability for transition pathways (Geels et al., 2020; McDowall, 2014) and 2) incorporation of narratives of transition pathways into energy modelling for policy (Foxon et al., 2010; Foxon, 2013; Foxon et al., 2013; Trutnevyte et al., 2014; Robertson et al., 2017; Li & Strachan, 2017).

Including a broader range of agents, structures and processes of governance, which could constrain possible infrastructure futures as much as physical assets, in techno-economic models and modelling helps improve the accuracy of models, offering a more representative application of the multiple dimensions of governance and how these might change. In addition, embedding this richer understanding of infrastructure governance in modelling can aid decision-making informed by techno-economic models on infrastructure, by identifying appropriate levers, scales and agents of governance.

Changes in infrastructure systems are an important element within transitions for sustainability (Loorbach et al., 2010; Markard, 2011; Roelich et al., 2015) and decisions for change in infrastructure systems share some distinctive characteristics with transitions thinking. In particular both settings suit, and arguably require, socio-technical analyses. Infrastructure systems, and their performance, are deeply intertwined with the social context and the many ways in which people interact with the material elements (Castán-Broto & Bulkeley, 2013; Geels, 2007; Van der Vleuten et al., 2013). The complexity and reach of these settings demand ways of bringing together data to assess systems to support decision-making. The incorporation of modelling into decision processes shows potential as an effective response to this challenge. However, the long timescales and the socio-technical nature of infrastructure settings also mean that modelling approaches and assumptions need to be carefully integrated into these complex settings for decisions.

Transitions research that brings qualitative and quantitative understandings together to examine pathways of development towards sustainability has used narratives/scenarios in conjunction with models (e.g. Foxon et al., 2010; Turnheim et al., 2015; Geels et al., 2020). And more recent work has advocated ‘dialogue’ (McDowall, 2014) or ‘bridging’ (Turnheim et al., 2015; Rosenbloom, 2017) processes to allow exchange of ideas/influence between two different approaches (e.g. techno-economic and socio-technical (Rosenbloom, 2017)) without fully bringing together (and therefore losing the benefit) of two fundamentally different approaches. This idea of bridging/dialogue is an important driver for the framework presented in this paper, which aims to structure interactions between qualitative, socio-technical governance thinking and a quantitative, techno-economic infrastructure model (in this case ITRC-MISTRAL's NISMOD).

Although the overlap between transitions thinking and the understanding needed to support infrastructure decisions is important, it is also important to acknowledge a key difference. Where scenarios approaches in transitions research, such as those referred to above, can be structured around ways to reach a sustainable future state, scenarios in considering infrastructure futures need to allow for different goals or visions of the future. This includes other areas of performance in addition to that of greenhouse gas emissions. This further emphasises the role of governance in infrastructure change as governance actors and processes shape priorities as well as possibilities for change. So, where models are being developed to aid decision-making, a structure is needed for connecting qualitative understanding of infrastructure systems and processes guiding their development with quantitative approaches to examining (and projecting) system performance. The methodological framework developed here structures the bridging between qualitative and quantitative approaches needed to connect governance and modelling performance in infrastructure. The framework is presented below and its application with NISMOD 2.0 developed in the ITRC-MISTRAL research project is described in section 4.

The framework is shown in figure 1. The four phases of this framework, and the principles behind them, are described in table 5. The four phases can be traversed moving from left to right starting from understanding current governance arrangements and then considering possible changes in governance, developing narratives and then developing ways to explore and assess those narratives through modelling. However, the framework can be applied in other ways. For example, stages two to four can be considered to represent linking stages that can be worked through iteratively to connect existing governance arrangements to an existing model of system performance. Whichever entry point is used for the framework, there are many opportunities for iterations between phases and incorporating co-development of understanding between different actors, as has been advocated by others (e.g. Kohler et al., 2020). The 'model' is also represented in the framework diagram to reflect that the four phases are conducted with reference to an existing or proposed model. The extent to which the model itself needs to be, and is possible to be, modified to effectively incorporate governance understanding is an important factor in shaping the activities conducted in working through the phases.

In addition to the four phases of the framework, figure 1 also shows the expected engagement intensity across the phases for two sets of actors (according to expertise and focus): 1) modellers/system experts and 2) civil society/decision-makers. This representation is intended to acknowledge that certain types of actors and expertise are associated with the two 'ends' of the framework and to bridge understandings of governance and of modelling for infrastructure these different types of knowledge and different perspectives will need to be brought together with the mix of actor involvement aligned with phase(s). This can be done in many different ways and it can be valuable to reflect on the extent of integration and reach of inclusion of different voices that is possible and appropriate within any given application.

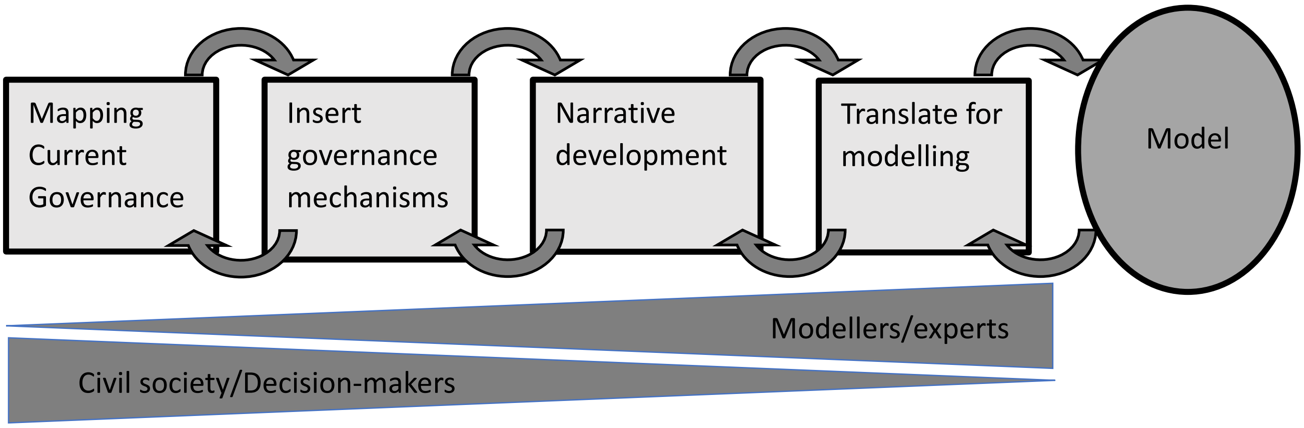

Figure 1 Methodological framework for governance-modelling integration

Table 5 Detail of methodological framework

	Phase Description	Phase Purpose
Mapping current governance	Representing current governance arrangements with respect to parameters of interest	Visualise and discuss current arrangements; highlights challenges/practices or prepares thinking around governance
Insert governance logics	Key ideas/principles for governance that highlight elements of different governance approaches	Allow stretching in thinking away from current governance structures – creating a space of future possibilities
Narrative development	Develop stories and scenarios for each of the governance logics	Explore governance logics and mechanisms in more detail. The set of narratives explain how potential changes from current governance arrangements could come about
Translate for modelling	Parameters selected or inserted into the model that can represent elements of the governance narratives. Set up of quantitative modelling of pathways to explore how narrative parameters could affect outcomes	To provide a bridge between modelling and the narratives. It should draw attention both to what can be modelled and what cannot. Sets up quantitative analysis and investigation of ranges of possible pathways

Using a framework like this is intended to highlight and allow reflection on decisions being made about complex socio-technical understandings within models. It provides a methodology for dialogue between modelling and a more qualitative understanding of the potential changes in governance that might emerge.

Section 4 describes and reflects upon the framework's initial application, developing governance thinking to accompany the development of NISMOD 2.0. In the case of NISMOD, the principles behind the computational model (though not its detailed development) are already in place. Even within this one context, there are many options and choices over how to address the different phases of the framework.

4 Combining governance and modelling within the development and application of NISMOD

In the use of this framework within ITRC-MISTRAL the core idea of the model, how it functions and what it will be used for, already exists. The ITRC-MISTRAL project builds on the national analysis in NISMOD 1.0 to develop NISMOD 2.0, which incorporates different scales of infrastructure change and levels of data. Moving scales of interest implies changes in centres and processes of decision-making and a need to acknowledge a range of governance activities in infrastructure provision and decisions. However, NISMOD 2.0 follows NISMOD 1.0 in its overall architecture of five distinct system models (Energy, Transport, Water, Waste and ICT) but with common input data and accompanying contextual scenarios for example on population change. Here we describe a range of activities conducted using the methodological framework introduced in section 3 to investigate how one might capture and use understanding of infrastructure governance (and its potential to change and direct change) alongside the techno-economic model being developed for UK infrastructure: NISMOD 2.0.

For the research within this context the framework is applied more or less in sequence for phases 1-4 (as shown in figure 1) with some iteration throughout. The form of the model is already in place so navigation of the framework involves an ongoing process of matching governance understanding to be useful in conjunction with this model. One important way in which the governance work was set up to fit with the needs of the model, is that the governance work was structured around the existing infrastructure sectors represented within the model (Energy, Transport, Water, Waste and ICT).

In the rest of this section activities conducted are presented by the phase of the framework they contributed to and, for clarity, the phases are addressed in number order (left to right in figure 1). The use of the framework was explored through three different types of approaches: a workshop to bring together a range of perspectives; governance-led desk-based research to map formal governance arrangements; and governance-modelling interactions, which were co-developed between actors in two areas of expertise. These approaches are used within several phases and across different sectors, as shown in figure 2; table 6, below, summarises and reflects on the three approaches and their application within the phases of the framework are described in the following sections.

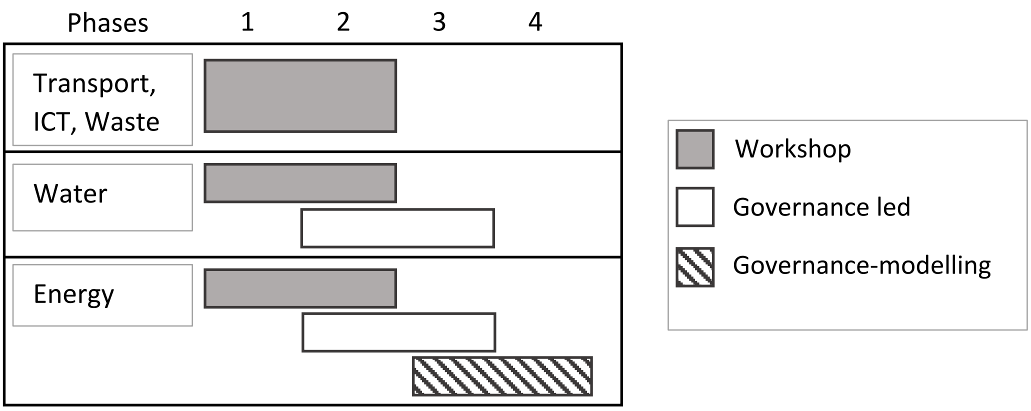

Figure 2 Phases trialled in the ITRC-MISTRAL project

Table 6 Summary of research approaches used within the application of the methodological framework for the ITRC-MISTRAL case

Description	Application in ITRC-MISTRAL	Strengths	Weaknesses
Workshop approach: bringing together key individuals (with a range of knowledge and perspectives) to co-create representations of governance	Workshop (October, 2017; ~40 participants) brought together academics, modellers and industry actors from infrastructure sectors. Activity was structured by sector (but with the five sectors represented in the same workshop) and focused on the generation of maps of current infrastructure governance	• Can capture informal as well as formal elements • Can use experience of participants to highlight relative importance/impact of elements discussed • Allows a range of perspectives to interact to produce representation	• Tends to be time constrained (time to generate representations and single occasion of workshop at point in time) • Can capture inaccuracies according to participants experience (e.g. where there's ambiguity or recent changes)
Governance-led approach: Desk based research to create governance representations of the context	Mapping (using the same structure as in the workshop) was generated by a governance researcher using a variety of sources (includes the option to build on workshop outputs)	• Can produce detailed representations with traceable sources of information • Interpretation of information can be done by a governance specialist	• Limited by the sources and perspectives available to an individual researcher • Time-consuming
Governance-modelling interactions: governance researchers and modellers interactions generate mutual understanding and to co-produce representations	Sharing of material and information between governance and modelling teams and interactions over that material and information. Further, governance & modelling specialists held a series of meetings to reflect on and generate narratives and modelling approaches	• In-depth interactions and co-development of detailed elements of modelling • Sharing of expertise and perspectives	• Demanding and time-consuming processes generating interdisciplinary understanding and common approaches • In the form used here contributions were limited to expert voices

4.1 Mapping current governance

A way of mapping current governance is developed to consider the governance structures and processes within which (and in response to which) infrastructure investment and development currently happens. There is a need to understand infrastructure decision-making in the UK at multiple levels as well as interactions between them. Focusing on actors in infrastructure governance a simple mapping framework was used (illustrated in figure 3) that includes three outline levels: subnational, national and international[3].

Maps like that shown in figure 3 have been generated within ITRC-MISTRAL using two main approaches: 1) co-creation of maps among sector-specialist groups (including modellers, academics and sector actors) 2) development of maps by using desk-based research. Reflecting on the five sector maps produced in the workshop setting, there is some degree of similarity between the sectors. For example, all of the maps contain relevant government departments, some reference to transnational

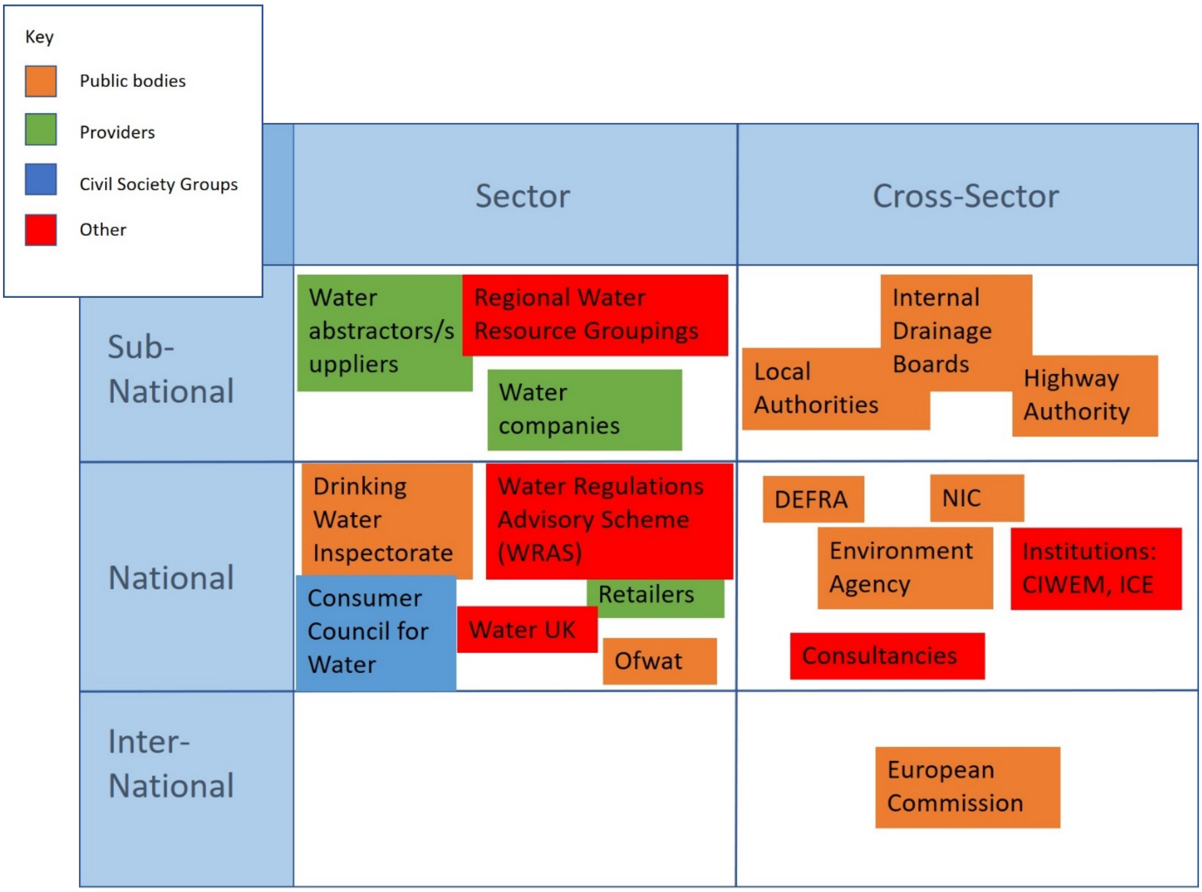

Figure 3 Mapping of key actors in the water sector of England and Wales from Workshop

organisations and appropriate regulatory organisation(s). There are also differences in structure and differences in emphasis. For example, regulation occurs in different structures in each sector. The transport sector is made up of several transport modes that function and are regulated separately – this is represented on the sector map. Further differences are shown in the roles played by certain cross-sector organisations – they may do different activities in different sectors. For example, Local

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[3] The various interpretations and contested nature of these terms are acknowledged by the authors and mapping participants were encouraged to start the process by considering what these categories referred to (and how they might be broken down further) in the context being examined.

Authorities are identified as being involved only in planning in ICT whereas they have a commissioning role in some sectors (e.g. Solid Waste/Transport).

This stage in the process outlined in section 3 has been used to initiate governance thinking starting from current governance arrangements and to provide (and document) a point of departure for developing governance futures. Through the discussion and positioning of actors on the maps, structures and processes of governance are also considered, preparing for the contemplation of changes in governance in phases 2 and 3. The maps themselves also provide a foundation for the application of different governance logics.

4.2 Governance mechanisms of change: generating scenarios

This phase is intended to stretch thinking about the ways in which governance might change. It generates governance narratives that consider how 1) definitions of actors 2) relationships between them and 3) governance processes might change. In the ITRC-MISTRAL project, three governance logics provide contexts for different governance mechanisms. These are applied to produce maps and narratives for governance futures. Governance mechanisms are the means of regulating or influencing behaviour to achieve desired goals (Gilliland et al. 2010). For example, within the Thousand Flowers logic described below, one governance mechanisms would be informal networks for local action such as the Transition Towns movement. Mechanisms could be formal, involving control and monitoring of the performance of actors through the setting of clear goals and targets (Eisenhardt 1989) or informal, based on relationships (Burket et al. 2012). The governance logics (outlined in table 7 below) were adapted from those developed in the Transition Pathways project (Foxon, 2013) - for investigating pathways to sustainability in electricity. Existing scenarios for infrastructure futures were reviewed and this project stood out in producing scenarios differentiated by the approaches to governance taken. As table 7 illustrates different governance logics present different mix of governance mechanisms.

Table 7 Governance logics (adapted from Transition Pathways project (c.f. Foxon, 2013))

Logics used to explore governance futures (adapted from those developed for scenarios for sustainable electricity in the Transition Pathways project – c.f. Foxon, 2013)
Market *Market Rules* envisions the broad continuation of what in several sectors is the current governance pattern. It means that the government specifies the high-level goals of the system and sets up the broad institutional structures, but these are based around the use of market arrangements where possible because they are held to be the most effective and efficient mechanism for delivering infrastructure services.
Central Co-ordination *Central Co-ordination* envisions greater direct governmental involvement in the governance of infrastructure systems. For example, in the energy sector, this involves the setting up of a Strategic Energy Authority and the use of central contracts for delivering new low carbon generation, including nuclear power, offshore wind and coal with CCS. The initial focus by government would be on overcoming blockages in the current system, by addressing provision constraints, planning issues, supply chains and skills, and introducing non-behavioural measures on the demand side. By leading on these measures and providing strong ‘technology push’ on key technologies, these actions would then legitimate further steps by government to influence lifestyles and behaviours.

Thousand Flowers
Thousand Flowers envisions a greater focus on more local, bottom-up diversity of solutions. This is driven by innovative local authorities and citizens groups, such as the Transition Towns movement, to develop local infrastructure facilities and services. A variety of more locally based technological and institutional solutions then begin to spring up, challenging the dominance of the existing large organisations and national focus of governance.

The co-development process within the workshop generated maps for each sector relatively quickly. This led to discussions about potential developments and obstacles for the three governance approaches. An example workshop map, for the Thousand Flowers governance logic applied to the energy system, is shown in figure 4 below. This map formed a starting point for further desk research to develop a set of governance narratives for the energy system. The development of these narratives is discussed in the next section.

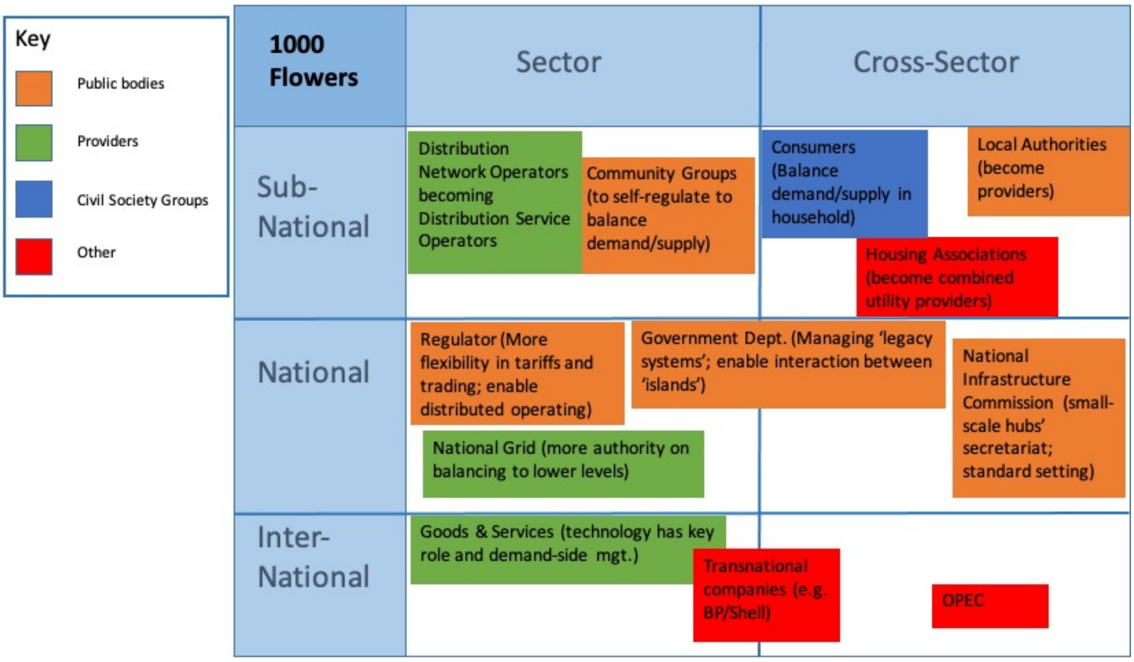

Figure 4 Energy workshop map for Thousand Flowers governance mechanisms

4.3 Narrative development

The generation of narratives from the governance logics introduced in stage two provides an important connection between the governance thinking and infrastructure modelling. This documents how governance could change, incorporating elements both that can and that cannot be modelled. These narratives move the thinking around actors and processes in the first stages towards considering what decisions and technologies might emerge in these different governance futures. They are an important tool for transparency in communication between governance and modelling specialists forming an important set of boundary objects between governance and modelling work.

In the ITRC-MISTRAL application of the framework narratives are sector focused and a set of three narratives, based on the governance logics and maps described above, can be produced for an infrastructure sector. These narratives are national in scope, but centres and scales of decision-making vary between governance logics; further, the impacts of the governance logics play out differently according to the organisational and technological norms of the sectors. The narratives used for ITRC-

MISTRAL were sector focused to reflect current expectations over governance and historical trajectories as well as the structure of the NISMOD models.

Two approaches have been used to produce sets of narratives for the water and energy sectors within the ITRC-MISTRAL project. Governance narratives for the future of the water sector were developed in a governance-led, desk research process. Inputs for the development of these narratives included a review of NISMOD 1.0 (discussed in section 2), in-depth discussion on the water modelling for NISMOD 2.0, and maps created for the water sector in phases 1 and 2 of the methodological framework.

Where modellers are ready to engage with governance thinking and more complex considerations of model development are needed, a more intensive interactive process between governance and modelling can be pursued. This approach was trialled in the generation of the three governance narratives for the energy system (see overview in Table 8). This involved the creation of initial narratives from the maps and discussions co-developed in the workshop and scenarios (for sustainable electricity by 2050) in the transition pathways project (Foxon, 2013). These narratives were shared with an energy modelling team and then discussed and reviewed with the potential capabilities of the model in mind. Revised narratives that were sensitive to and ready to feed into the translation process could then be produced.

This has the benefit of deeper and longer-term sharing of understanding that can open up more innovative approaches which both groups are committed to; it also can produce longer-term impacts for both groups in understanding the other's working. However, this level of interaction is not always feasible and can be relatively high risk as it involves considerable investment of time and commitment from across the project. The context for combining governance and modelling work is important in developing the narrative creation process.

Table 8 Overview of narratives developed for energy system

	Market	Central	Thousand Flowers
Governance overview	• Government specifies high level goals • Distribution networks franchised • Consumers choose provider and type of service contract • Markets (wholesale and consumer) regulated by national organisation	• Strategic Energy Authority (directed by government priorities and budget) has oversight and development of energy as a national system • It works closely with generation, transmission and distribution operators (where possible, divisions within a national operator) and a national regulator	• Energy supplied through a combination of household-scale installations, municipal provision, small commercial/collective endeavours and portable energy • National gas and electricity transmission networks are phased out for domestic use and distribution networks are operated by collectives/municipal organisations (taken over ownership from the private sector).

Priorities to be reflected in system development	• Gain and retention of customers • Appealing and profitable service contracts • Meeting emissions and safety requirements (from regulator)	• National emissions targets • Reliable (national) supply • Costs of energy delivery	• Local civic priorities including fair access and emissions targets • Platforms, of business models and access to expertise, to connect and co-ordinate producers and consumers
System change	• Developed with consumer focus • Spaces for consumer choice and abilities to express preferences needed • Co-ordination and funding vehicle barriers to capital intensive developments such as nuclear and CCS • Demand and supply could be addressed but business models and regulatory support needed	• Developed as national system with SEA as system builder, specifying projects • Expect minimal influence on demand • Could cope with capital intensive developments such as nuclear and CCS • Expect exploitation of diversity of sources across UK (economies of scope in generation)	• Developments connected to place (in terms of physical geography, expertise and population needs) • Supply and demand closely connected (would expect interventions addressing both) • Expect micro (household) and locally suited developments (municipal investments/storage and co-ordination solutions)

4.4 Translation: governance thinking into model analysis

This phase in the methodological framework highlights the decisions being made to incorporate governance variations into the modelling process. This stage covers the processes and means for setting and assembling sets of parameters for relevant variables to represent scenarios in model runs. This includes decisions over adding/removing variables from the model to accommodate variety contained in the governance narratives and processes of sorting through elements within the narratives that can and cannot be incorporated into the modelling. Whether this stage is overseen by modelling teams interpreting the narratives produced by others or it is a more collaborative process, it is an important phase within the framework to highlight the importance of reflection and justification over the choices made.

In ITRC-MISTRAL this stage was conducted for the energy sector and translation was co-developed between governance and modelling researchers through a series of meetings. Matching between the three governance narratives and the energy system model was conducted in an iterative way. One key step proposed for integration was that the modelling be broken down into stages with initial governance arrangements and investment expectations to input into the model to run to 2030 and further developments and decisions using governance narratives to be generated phase by phase. After sharing and revision of the governance narratives they were broken down further by noting that the different central actors (identified in the respective narratives) brought with them both different processes for system development and different priorities for system performance. These distinctions guided the definition of the expected investment mix to be incorporated into the model (illustrative interventions for development under centralised governance are shown in the box below).

- Little emphasis on energy efficiency / demand reduction - emphasis in this pathway is on investing in energy sources and networks to meet demand.
- Phase out of coal power stations without carbon capture and storage (by 2025)
- New Nuclear programme (10 large Hinkley sized reactors come online between 2025 and 2035)
- Offshore wind continues to grow to double present capacity in the 2020s

- Electricity storage capacity increased - large scale grid connected batteries (Up to 8GW by 2030)
- Heating systems progressively moved to hydrogen through national programme of gas network conversion, starting in 2030. Hydrogen produced by electrolysis from large scale nuclear/ wind and gas (with carbon capture and storage)
- Transport moves towards electric - recharging network for road vehicles (meets current UK plans for petrol/diesel phase out by 2040) and electric supply for rail.

Box 1 Illustrative interventions for energy under centralised governance mechanism

This process found that although there were approaches available to represent the Market and Centralisation governance logics in modelling of energy within NISMOD 2.0, the Thousand Flowers logic, focusing on more localised centres of governance, was much more difficult to incorporate. This governance approach is much further away from existing conventions considering national infrastructures. Incorporating this alternative approach may have much to offer for considering infrastructure futures and for providing potential for challenging conventions in infrastructure decisions and enabling alternative paths of development. However, as demonstrated in the analysis described in section 2 and due to having been built from understanding of existing infrastructure sectors, the NISMOD model has embedded within it sets of governance assumptions that present a barrier to fully depicting this alternative governance approach.

The collaborative approach, and the increased understanding of modelling and governance interdependence, led to the proposal and outline of a module within the model's decision-layer to incorporate the different approaches inherent in the three governance logics directly into modelling runs that could be developed in a future project. This addition to the model and its logic (in being positioned within the decision-layer) would also build upon the phased approach developed in the collaboration at this stage. It is needed to better represent the Thousand Flowers governance approach in future analyses. Such a module should also allow governance variations to be incorporated into everyday use of the model and push the consideration of governance arrangements into modelling scenarios.

This phase of the framework incorporates the generation, adaptation and application of models to analyses incorporating qualitative understanding of possible variation (here in the case of infrastructure governance) with quantitative representation and analysis of development. In the ITRC-MISTRAL research, setting up the model with some relatively minor adaptation to allow governance incorporation was anticipated; however, as described above, more significant adaptation, in the form of an additional decision module is needed. It is worth noting that the process of integrating governance thinking into model analysis was a new intervention within the ITRC-NISMOD project and as such operated within its limits. Although the modelling involved a degree of 'reality checks' through the input of decision-makers and infrastructure experts at the start of the modelling, it is possible and recommendable to build in more extensive co-development opportunities through further interactions between decision-makers, civil society, infrastructure experts and the modellers throughout all phases of the model. From experience such continuous engagement is resource and time intensive, and the extent of its merits will depend on the context of the model and potential model users.

4.5 Reflection on the interaction of the four-phase process with the model

As highlighted above, in ITRC-MISTRAL NISMOD, represents a pre-existing modelling approach that has been developed without incorporating governance variation into the model structure. The four phases discussed above were traversed to extend the model's ability to consider wide-ranging infrastructure futures by integrating governance thinking into analyses.

In other applications of the methodological framework a model may be developed in response to the integration of different approaches, such as governance, with techno-economic modelling or significant model restructuring. In this case, working through the phases created a blueprint for modification of the model, in the form of additions to the decision-layer.

There are two routes of development presented by the ITRC-MISTRAL governance-modelling collaboration. Firstly, the model can be used to explore the infrastructure performance implications of potential governance futures – highlighting areas of risk and potential strengths offered with different approaches. However, the incorporation of governance elements into the decision-layer of the model would provide the capacity to consider governance variations (and innovations) as factors in infrastructure development, and potential levers for change, where the model is being used to assess and investigate the implications of technology and policy developments on infrastructure performance.

The value of developing and applying the four-phase process was in designing and partially testing an accessible process for embedding governance in the modelling, particularly in the context of infrastructure, rather than in generating specific "results" from exploration of governance arrangements in the energy, water and transport sectors.

5 Discussion

Reporting on research investigating connections between a techno-economic model to support decisions in UK infrastructure development and understanding of infrastructure governance, this paper presents and discusses a methodological framework to critically combine qualitative approaches to governance and quantitative modelling capability for decision-making. Three stages of this research are discussed further and brought together here: 1) governance analysis of application of NISMOD 1.0, a multi-sector model of UK infrastructures; 2) development of a methodological framework; and 3) a trial application of the framework in engaged research with stakeholders and model developers.

A techno-economic model of system performance, like NISMOD, will contain assumptions over processes and priorities of system development connected to the period, perspectives and techniques of model development. These effects are shown for NISMOD 1.0 in an analysis of its use in the National Needs Assessment (ICE, 2016) (section 2). This highlights the risks of not considering governance arrangements critically in model development and analysis. To acknowledge variety in priorities and potential changes in infrastructure development processes, modelling analyses need to be able to check (and adjust) embedded infrastructure governance assumptions. Further, in the case of this national infrastructure model, the long timescales being modelled and the combined model for systems currently governed separately add uncertainties over what governance arrangements might be 1) possible and 2) likely.

The retrospective governance analysis of the application of NISMOD 1.0 indicates the need for a more integrated and interactive approach of considering governance with model development and use. It also highlights the time and level of detail needed to investigate embedded assumptions in large and complex techno-economic models like this. Governance concerns hadn't been considered and documented within the initial development of NISMOD 1.0 and there was limited detail on these issues in the NNA policy report. The analysis described in section 2 drew upon internal documentation of the modelling and discussions with modellers in addition to the published policy report (ICE, 2016). So, where these interdisciplinary challenges (here combining socio-technical understanding with techno-economic approach) are addressing large and complex models, this shows the value of embedding researchers (in this case socio-technical researchers) within the model development team.

In this case there was a small team of socio-technical researchers working with a much larger group of modelling focused researchers. The methodological framework described in section 3 was developed to guide and describe interactions between socio-technical and techno-economic approaches. Drawing upon recent transitions and energy research considering and modelling pathways of system development, the framework represents a 'bridging' (Turnheim et a., 2015; Rosenbloom, 2017) mechanism between these distinct approaches (techno-economic and socio-technical (e.g. Rosenbloom, 2017)) and it structures a process of interaction between them. It is also akin to the 'dialogue' approach advocated by McDowall (2014) in his hybrid approach to assessing hydrogen transitions.

There are several potential benefits of a methodological framework like the one developed here (section 3) to consider governance arrangements and possibilities within the setup of analyses to assist policy decision-making.

- Following the framework requires consideration of governance arrangements from an early stage in the research and forces engagement with these issues.

- The framework provides a communication tool, showing governance concerns and highlighting modelling constraints to all involved stakeholders
- Working with the framework drives transparency over the questions that need to be addressed to bring governance understanding into the analysis and it guides explicit characterisation of the decisions taken and assumptions made in the analysis

Further, such a framework can be used to facilitate (interdisciplinary and transdisciplinary) stakeholders working together for a range of activities. Research activities could include: analysis for policy advice (whether that process is to be led by academic researchers or policy actors or co-developed); research co-developing scenarios to be assessed using the modelling; model development (keeping policy uses for the model in mind). However, there are also engagement activities working with a diverse group of (non-specialist) actors – perhaps to develop/test futures scenarios; the framework could be used here to show (and check) how different voices have been included and interpreted within modelled scenarios.

The application and trial of the methodological framework to use and collate a range of methodological approaches developing and connecting governance-thinking with the modelling showed the potential of combining different approaches to strengthen the research process. For example, overlapping the use of workshop and governance-led approaches (see table 6). The co-creation approaches to the governance mapping and governance variation stages that were trialled within ITRC-MISTRAL provide an early example of the types of processes required and highlight some of their strengths and weaknesses and the value of this framework for providing transparency and reflexivity in the combination of such approaches.

Activities focusing on potential governance mechanisms (phase 2 - widening viewpoints) and how they might fit with system(s) (phase 3- narratives) worked with 'governance logics' developed in the Transition Pathways project (Foxon, 2013; Foxon et al., 2013). These governance logics (Market Rules, Central Co-ordination, Thousand Flowers) were developed to differentiate scenarios in terms of variations in governance approaches. They were applied here for the same reason and were adapted and trialled for application across multiple infrastructure sectors. The maps, narratives and discussions produced in the course of this research demonstrated their usefulness beyond energy sectors. They were used to initiate structured imagination of governance arrangements beyond current and recent structures.

The Thousand Flowers logic, that captures local, community-based modes of governance, provoked consideration of governance arrangements that are rarely linked to infrastructure when it is discussed at a national level. Pursuing this thinking through phases 3 and 4 showed that the NISMOD model was not able to work through scenarios for this governance approach. This highlights the invisibility of these governance arrangements - as routes for system changes and for the developments and priorities that are associated with them – to policy and systems analysts. A sector that developed important governance arrangements in this mode would become mis-represented within cross-sector analyses where model structure excludes it. Further, the inability of the model to incorporate this governance mode excludes governance approaches of this type from the possibilities considered to enable innovation for transition. Considering this governance logic, and the intended use of the NISMOD model, was important in driving the creation of a blueprint for an additional module to be added to the model to aid the capture of governance variations. A key importance and novelty of this approach is offering a framework for embedding broader governance arrangements across multiple infrastructure sectors in modelling, addressing key weaknesses in modelling such as invisibility of actors and governance actions beyond the national level.

The integrated approach pursued here, embedding socio-technical researchers within a model development project, is one potential route for improving policy decision-making socio-technical systems and transitions. It can be considered alongside approaches such as developing socio-technical models to accompany or compete with techno-economic approaches (e.g. Kohler et al., 2020) and research efforts to integrate other methods into analysis alongside techno-economic modelling (e.g. ethnography as 'thick-data' to accompany agent-based modelling in complementing techno-economic analysis, Hiteva et al. 2018). Advantages of the approach used in this research include 1) the ability of researchers working alongside a complex techno-economic for a period of time to become familiar with its strengths and weaknesses and 2) the adaptation of accepted and respected processes for evidence in policy-decisions has the potential to assist access, of these socio-technical approaches, for policy-makers and policy processes. This approach could be used to improve the governance sensitivity and robustness of other types of techno-economic modelling, beyond the infrastructure sectors, and could be particularly useful in exploring interdependencies between systems and nexus relationships at multiple scales (including regional and urban, and their growth in importance through devolution).

Working as part of a model development process is an important window of opportunity for influencing decision-processes and what concerns are included, however it is also demanding in terms of fitting learning and engagement around socio-technical approaches into a busy and focused development environment. This approach is resource intensive and places pressure on interdisciplinary working that is not always easy to pursue. An important constraint to following this kind of approach is the access to, and capacity of, model developers whilst they are developing new and ambitious models.

6 Conclusion

Governance processes and structures are important elements that shape the development of socio-technical systems such as infrastructure sectors; they need to be considered in the development of infrastructure futures. For infrastructure, as for other areas, techno-economic modelling approaches are prevalent in policy decision-making. The analysis of the use of techno-economic modelling within the UK's National Infrastructure Assessment (presented in section 2) shows the importance of incorporating governance thinking into modelling analyses to support decisions. One approach for incorporating governance (or other socio-technical) concerns in analysis and processes for policy decisions is to engage with techno-economic models, their development and application in analyses. This paper proposes a framework for connecting governance thinking with modelling analyses for infrastructure decisions and policy and illustrates its application within the development of analyses using NISMOD 2.0.

The framework offers potential for improved integration of modelling into infrastructure policy and as the basis for future research exploring development pathways for infrastructure considering the co-development of technological advances and appropriate governance arrangements. Its use with NISMOD 2.0 has highlighted the potential for exploring governance variations with techno-economic development options – offering both research and policy opportunities. As it has been developed within this research, the framework proposed can be used in conjunction with the NISMOD 2.0 model in the UK or similar national models developed for other contexts improve infrastructure policy decisions by national sectoral organisations or cross-sectoral actors such as the National Infrastructure Commission. There is further potential to use the framework to develop approaches for different scales, sectoral arrangements and modelling techniques and to structure meaningful engagement processes that use modelling capabilities – extending their use to link views of a range of actors and potentially provide one mediation function towards vision development for these socially important systems.

For sustainability transitions and for broader societal concerns within infrastructure development, the integration of socio-technical approaches and governance understanding within the development and application of techno-economic analysis with powerful modelling tools is one important route to support and improve policy decisions. However, for both the approach of embedding socio-technical researchers in model development projects and the application of the methodological framework developed here, a key limitation is resources and engagement levels required. This research project provides an example of an integrated approach to socio-technical and modelling research activities and the processes and methodological framework described here can offer a starting point for others.

However, if successfully applied it can greatly aid all four stages of transitions management at the national level and within emerging scales of importance in the context of infrastructure (such as city-regions). For example, by elaborating more sophisticated and complex perspectives of actions, actors, and systems, which could in turn help mobilize a broader group of actors around infrastructure governance. Further research could examine how the integrated approach discussed here could embed more reflexive practices of vision-building and decision-making for sustainability management across different sectors and scales.

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References

BEIS (Department of Business, Energy and Industrial Strategy) (2017). Industrial Strategy: building a Britain fit for the future. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/664563/industrial-strategy-white-paper-web-ready-version.pdf (accessed 31 July 2020)

BEIS (Department of Business, Energy and Industrial Strategy) (2019a) Carbon capture, usage and storage (CCUS): business models https://www.gov.uk/government/consultations/carbon-capture-usage-and-storage-ccus-business-models (accessed 13 August 2020)

BEIS (Department of Business, Energy and Industrial Strategy) (2019b). News Story: UK becomes first major economy to pass net zero emissions law. https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law (accessed 5 August 2020)

Burkert, M., Ivens, B.S., & Jialu, S. (2012). Governance mechanisms in domestic and international buyer–supplier relationships: An empirical study, Industrial Marketing Management, 41 (3), 544-556.

Castán-Broto, V., & Bulkeley, H. (2013). Maintaining climate change experiments: Urban political ecology and the everyday reconfiguration of urban infrastructure. International Journal of Urban and Regional Research, 37(6), 1934-1948.

Eisenhardt, K.M. (1989). Agency theory: An assessment and review. Academy Of Management Review 14 (1), 57-74.

Foxon, T. J. (2013). Transition pathways for a UK low carbon electricity future. Energy Policy, 52, 10-24.

Foxon, T. J., Hammond, G. P., & Pearson, P. J. (2010). Developing transition pathways for a low carbon electricity system in the UK. Technological Forecasting and Social Change, 77(8), 1203-1213.

Foxon, T. J., Pearson, P. J., Arapostathis, S., Carlsson-Hyslop, A., & Thornton, J. (2013). Branching points for transition pathways: assessing responses of actors to challenges on pathways to a low carbon future. Energy Policy, 52, 146-158.

Geels, F. W. (2007). Transformations of large technical systems: A multilevel analysis of the Dutch highway system (1950-2000). Science, Technology, & Human Values, 32(2), 123-149.

Geels, F. W., McMeekin, A., & Pfluger, B. (2020). Socio-technical scenarios as a methodological tool to explore social and political feasibility in low-carbon transitions: Bridging computer models and the multi-level perspective in UK electricity generation (2010–2050). Technological Forecasting and Social Change, 151, 119258.

Gilliland, D.I., Bello, D.C., & Gundlach, G.T. (2010). Control-based channel governance and relative dependence. Journal of the Academy of Marketing Science, 38 (4), 441-455.

Goldthau, A. (2014). Rethinking the governance of energy infrastructure: Scale, decentralization and polycentrism. Energy Research & Social Science, 1, 134-140.

Hall, J. W., Tran, M., Hickford, A. J., & Nicholls, R. J. (Eds.). (2016). The future of national infrastructure: A system-of-systems approach. Cambridge University Press.

Hiteva, R., Ives, M., Weijnen, M., & Nikolic, I. (2018). A complementary understanding of residential energy demand, consumption and services. In Advancing Energy Policy (pp. 111-127). Palgrave Pivot, Cham.

HM Treasury (2017). National Infrastructure Commission framework document. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/585374/NIC_framework_document_web.pdf (accessed 31 July 2020)
HM Treasury (2018). National Infrastructure Commission welcomes Sir John Armitt as new Chair https://www.gov.uk/government/news/national-infrastructure-commission-welcomes-sir-john-armitt-as-new-chair (accessed 5 March 2020).

HM Treasury & IPA (2016). National Infrastructure Pipeline 2016. https://www.gov.uk/government/publications/national-infrastructure-pipeline-2016 (accessed 11 March 2020)

Hof, A. F., van Vuuren, D. P., Berkhout, F., & Geels, F. W. (2020). Understanding transition pathways by bridging modelling, transition and practice-based studies: Editorial introduction to the special issue. Technological Forecasting and Social Change, 151, 119665.

ICE (Institute of Civil Engineering) (2016). National Needs Assessment - A Vision for UK Infrastructure. https://www.ice.org.uk/getattachment/news-and-insight/policy/national-needs-assessment-a-vision-for-uk-infrastr/National-Needs-Assessment-PDF-(1).pdf.aspx#_ga=2.237718976.1927464910.1583450411-2059450992.1583450411 (accessed 5 March 2020)

Köhler, J., Turnheim, B., & Hodson, M. (2020). Low carbon transitions pathways in mobility: Applying the MLP in a combined case study and simulation bridging analysis of passenger transport in the Netherlands. Technological Forecasting and Social Change, 151, 119314.

Li, F. G., & Strachan, N. (2017). Modelling energy transitions for climate targets under landscape and actor inertia. Environmental Innovation and Societal Transitions, 24, 106-129.

Loorbach, D., Frantzeskaki, N., & Thissen, W. (2010). Introduction to the special section: Infrastructures and transitions. Technological Forecasting and Social Change, 77(8), 1195-1202.

Markard, J. (2011). Transformation of infrastructures: sector characteristics and implications for fundamental change. Journal of Infrastructure Systems, 17(3), 107-117.

McDowall, W. (2014). Exploring possible transition pathways for hydrogen energy: a hybrid approach using socio-technical scenarios and energy system modelling. Futures, 63, 1-14.

Nilsson, M., Dzebo, A., Savvidou, G., & Axelsson, K. (2020). A bridging framework for studying transition pathways–From systems models to local action in the Swedish heating domain. Technological Forecasting and Social Change, 151, 119260.

Robertson, E., O'Grady, Á., Barton, J., Galloway, S., Emmanuel-Yusuf, D., Leach, M., Hammond, G., Thomson, M. & Foxon, T. (2017). Reconciling qualitative storylines and quantitative descriptions: an iterative approach. Technological Forecasting and Social Change, 118, 293-306.

Roelich, K., Knoeri, C., Steinberger, J. K., Varga, L., Blythe, P. T., Butler, D., ... & Purnell, P. (2015). Towards resource-efficient and service-oriented integrated infrastructure operation. Technological Forecasting and Social Change, 92, 40-52.

Rosenbloom, D. (2017). Pathways: An emerging concept for the theory and governance of low-carbon transitions. Global Environmental Change, 43, 37-50.

Saltelli, A., Bammer, G., Bruno, I., Charters, E., Di Fiore, M., Didier, E., Nelson Espeland, W., Kay, J., Lo Piano, S., Mayo, D., Pielke Jr, R., Portaluri, T., Porter, T.M., Puy, A., Rafols, I., Ravetz, J.R., Reinert, E., Sarewitz, D., Stark, P.B., Stirling, A., van der Sluijs, J. & Vineis, P. (2020). Five ways to ensure that models serve society: a manifesto. Nature 582, 482-484 doi: 10.1038/d41586-020-01812-9

Trutnevyte, E., Barton, J., O'Grady, Á., Ogunkunle, D., Pudjianto, D., & Robertson, E. (2014). Linking a storyline with multiple models: a cross-scale study of the UK power system transition. Technological Forecasting and Social Change, 89, 26-42.

Turnheim, B., Berkhout, F., Geels, F., Hof, A., McMeekin, A., Nykvist, B., & van Vuuren, D. (2015). Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. Global Environmental Change, 35, 239-253.

Van der Vleuten, E., Högselius, P., Hommels, A., & Kaijser, A. (2013). Europe's Critical Infrastructure and Its Vulnerabilities—Promises, Problems, Paradoxes. In The Making of Europe's Critical Infrastructure (pp. 3-19). Palgrave Macmillan, London.