# Assessing the Long-Term Performance of Cross-Sectoral Strategies for National Infrastructure

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**Abstract:** National infrastructure systems (energy, transport, digital communications, water, and waste) provide essential services to society. Although for the most part these systems developed in a piecemeal way, they are now an integrated and highly interdependent "system of systems." However, understanding the long-term performance trajectory of national infrastructure has proved to be very difficult because of the complexity of these systems (in physical and institutional terms) and because there is little tradition of thinking cross-sectorally about infrastructure system performance. Here, a methodology is proposed for analyzing national multisectoral infrastructure systems performance in the context of uncertain futures, incorporating interdependencies in demand across sectors. Three contrasting strategies are considered for infrastructure provision (capacity intensive, capacity constrained, and decentralized) and multiattribute performance metrics are analyzed in the context of low, medium, and high demographic and economic growth scenarios. The approach is illustrated using Great Britain and provides the basis for the development and testing of long-term strategies for national infrastructure provision. It is especially applicable to mature industrial economics with a large stock of existing infrastructure and challenges of future infrastructure provision. **DOI: 10.1061/(ASCE)IS.1943-555X.0000196.** 

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## Challenges of National Infrastructure Provision

Infrastructure is essential for human wellbeing and economic productivity in modern industrialized society. However, in many advanced economies, infrastructure provision is facing serious challenges. There is growing demand for infrastructure services from increasingly aging assets. Consider, for example, the 31,000 km of water mains in London, nearly half of which are over

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100 years old (Thames Water 2011). For many infrastructure sectors, high levels of investments are needed to ensure that infrastructure systems can meet ever-increasing demand and provide reliable, cost-effective, and high-quality services. For example, in the *2009 Report Card for America's Infrastructure*, ASCE estimates that improving U.S. infrastructure to a good condition would require $2.2 trillion in investments over the subsequent five years (ASCE 2009). The 2013 report card paints a similar picture; for example, it estimates that urgent investments in drinking water pipes alone will require approximately $1 trillion spread over the next 25 years (ASCE 2013). Further, infrastructure shapes many of the interactions between society and the natural environment: infrastructure is one of mankind's most visible footprints on the Earth's surface and is a key determinant of the quantity and type of pollutants (including greenhouse gasses) released into the natural environment.

The evolution of infrastructure from a series of unconnected structures in the early twentieth century to the present interconnected networks has resulted in increased complexity and interdependence of infrastructure systems. The shift towards liberalization, private provision, and competition in infrastructure sectors has led to a more complex governance landscape where a range of actors are involved in infrastructure planning and decision making.

Decision makers on the whole recognize the long lead times and potential lock-in of infrastructure planning decisions. However, they are not well equipped to analyze the implications of their decisions in a complex adaptive system whose performance will be shaped by factors that are often severely uncertain in the long term. Interdependence between infrastructure sectors adds to the uncertainty in the strategic planning of infrastructure. Consultation with infrastructure planners, owners, and operators has revealed a series of strategic questions that they currently struggle to analyze:

1. What are the implications of the growing demand for infrastructure services?
2. What are the implications of constrained investment in infrastructure capacity?
3. What are the implications of changing energy prices and potential constraints on carbon emissions in future?
4. What are the possibilities for a decentralized infrastructure system? and
5. What are the implications of interdependence between infrastructure sectors?

This paper reports on the first step in a research program to develop methodology for long-term planning and assessment of infrastructure systems. The methodology presented has been developed for a rapid preliminary assessment, so is known as fast-track analysis (FTA). It is illustrated using Great Britain (England, Wales, and Scotland) as an example. Although in some respects based on existing conceptual frameworks for scenario analysis and sector assessment models, the analysis, for the first time, applies consistent methodology across different infrastructure sectors at a national scale and tests alternative cross-sectoral strategies for national infrastructure provision.

## Analyzing Infrastructure System of Systems

Over the last decade, much of the literature on broad-scale cross-sectoral infrastructure assessment focused on assessing the risk of failure of critical infrastructures. For example, Haimes and Jiang (2001) developed the input-output inoperability model to evaluate the effects of the interdependent failure between infrastructure sectors based on the economic theories of Wassily Leontief. Later, developments of this model included the dynamic input-output model (Haimes et al. 2005), and the multiregional inoperability input-output model (Crowther and Haimes 2010). Other examples of models and simulation tools for analyzing critical infrastructure (including their interdependencies, vulnerabilities, and impact from disruptions in service) include those developed by the U.S. National Infrastructure Simulation and Analysis Center at Sandia National Laboratory under the direction of the Department of Homeland Security's Office of National Infrastructure Protection. The focus on assessing critical infrastructure risks is reflected in the *National Infrastructure Protection Plan* (U.S. Department of Homeland Security 2009), which develops a unifying plan for the protection of critical infrastructure protection across sectors. In contrast to the developments in evaluating the risk of interdependent infrastructure failure, there has been significantly less focus on the cross-sectoral analysis of infrastructure services in terms of the capacity of infrastructure systems in the face of changing future patterns of demand. The methodologies that have been developed tend to focus on the near term, on single sectors, or on single big events such as those discussed in Karlaftis and Peeta (2009).

System of systems (SoS) frameworks provide a useful approach to analyzing infrastructure systems because SoS address a class of complex systems that are themselves composed of complex constituent components. Jamshidi (2008) defines SoS as "large-scale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal." System of systems methodologies vary significantly and have been applied in a variety of contexts, including the sector-specific application to the electric power grid (Korba and Hiskens 2008) and air transportation systems (DeLaurentis 2008). However, less developed are methodologies that apply the SoS approach to all infrastructure systems. The approach is challenging in part because sector-specific models often take fundamentally different modeling approaches that do not have common goals (Thissen and Herder 2008).

In this paper, the authors develop a methodology that uses a SoS methodological approach to support decision making for national infrastructure provision. This is an inherently multiattribute decision problem that seeks to provide requisite system performance with respect to service reliability, cost, and environmental impacts.

## Long-Term Scenario Analysis

Infrastructure planners and designers are faced with the fundamental problem that the systems they are designing will last for many decades into the future, but on those timescales, social, economic, technological, and climatic changes, among others, will take place on a scale that is very difficult to predict. Until relatively recently, designers have tended to assume deterministic, if conservative, demand conditions. Increasingly, scenario analysis (sometimes referred to as scenario planning), has been adopted as a tool for evaluating future system performance across a range of plausible futures. Scenarios are often thought of as narratives that describe the impact of selected conditions and implications of alternative futures for the policies under consideration (Bodde 2007). A scenario can be described as an "if-then" proposition, representing an initial state and future states created by defined key driving forces (Alcamo and Henrichs 2008). They are constructed either by an extrapolation of current trends or consideration of systemic step changes (Wollenberg et al. 2000). Scenario analysis is particularly useful for management of the so-called ignorance quadrant of the risk space (e.g., Stirling 1999; Sovacool 2011), and where there is high complexity and future uncertainty (Schoemaker 1993; Wollenberg et al. 2000). Thus, decision makers can evaluate present decisions based on different possible futures (Wollenberg et al. 2000).

## Methodology

The FTA is a rapid assessment that enables the performance evaluation of long-term, cross-sectoral strategies for regional to national infrastructure over a range of possible futures. Rapid assessments such as the FTA provide important insights to decisions makers on policy direction and investment priorities prior to the effort involved in more-detailed studies. The FTA is developed from a service-based perspective of infrastructure provision. The method provides insights into the capacity of infrastructure systems to deliver required services now and in the future, in the context of changing demands and capacity of infrastructure systems. Importantly, the scenario approach seeks to illuminate rather than optimize system performance, providing insights rather than prescriptions for decision makers, planners, and designers. The authors adopt a multiattribute definition of performance, which incorporates dimensions of service reliability, cost, and environmental impact.

The infrastructure sectors included in this assessment are energy, transportation, water, and waste. Digital fixed and mobile communications systems and data processing are excluded from this set of infrastructures, even though they are now ubiquitously embedded in all other infrastructures and, in their own right, are essential for societal function. However, the planning cycle for these systems is much less long-term compared with other sectors, and for the most part information and communications technologies (ICT) infrastructure is not subject to the same demand constraints as the other four sectors, so was excluded from explicit treatment in the FTA. The authors touch on ICT in the concluding discussion.

### *Service-Based Approach to Infrastructure Provision*

Analysis of infrastructure often begins with the hardware that constitutes infrastructure assets: power stations, highways, reservoirs, treatment works, pipes, and cables. Starting with physical infrastructure assets is natural, as they are readily identifiable and represent the accumulated capital. However, such an approach distracts from the purpose of infrastructure, which is to provide services to people and the economy. It also tends to emphasize the flux of resources through infrastructure networks (e.g., gas, water) and implies that increasing flux represents improved infrastructure provision (and perhaps also increased revenue for the utility providing that resource). Again, such a perspective is undesirable, because improved service provision does not necessarily need to be accompanied by increased resource use (e.g., improved service may result from efficiency increases).

In contrast to this view, a service-based perspective on infrastructure provision emphasizes the purpose of infrastructure provision rather than the physical infrastructure and resource fluxes. Thus, infrastructure systems can be described in terms of their capacity to supply infrastructure services and the demand for infrastructure services that they are expected to satisfy. Both capacity and demand vary in time and geographically. The infrastructure sectors are interdependent in that they place demands on one another (e.g., all of the systems require energy infrastructure to function). Another source of interdependence is that components of demand for different infrastructure services are correlated (e.g., increased temperatures imply increased demand for both water and energy because of cooling requirements). The capacity of infrastructure services is the limit to the amount of demand that can be sustained.

Demand is influenced by economic, demographic, behavioral, and technological factors as well as by the existence of a specific infrastructure service. Further, demand may be modified by the capacity of the infrastructure (e.g., in the transportation sector, where capacity affects journey times and comfort). This is particularly true at times when demand approaches capacity limits. Pricing mechanisms and other policies may also serve to modify and reduce demand. Thus, capacity and demand are not generally independent, though they may be treated as such in special cases. Under normal operating conditions, the capacity of infrastructure services will be equal to or greater then demand. However, insufficient capacity compared with demand leads to inadequate service provision, e.g., in terms of traffic congestion or water shortages.

### *Exploring Future Uncertainties through Scenarios*

As previously discussed, a long-term perspective in infrastructure analysis and planning is necessary, but brings with it significant uncertainties. It is important to understand how future plans may be vulnerable to such uncertainties, and, where possible, to seek decisions that are robust to those uncertainties. To explore the uncertainty in the long term, the FTA methodology adapts an approach to long-term policy analysis described by Lempert et al. (2003), who develop a range of plausible scenarios to explore the performance of alternative strategies with respect to that range of possible futures. In the work of Lempert et al. (2003), the performance of a set of policy options is assessed with respect to a range of possible future conditions. The aim of exploring this space of possible future conditions is to identify vulnerabilities and opportunities to seek strategies that are robust against uncertainty. Within each infrastructure sector, the scenario construction enables the evaluation of common key drivers of change that impact the future demand and capacity of infrastructure. The goal of scenario analysis as used in the FTA is to determine the cross-sectoral infrastructure plans (i.e., strategies) that are robust across multiple scenarios. Robust strategies are those that perform well under multiple possible futures (Lempert and Schlesinger 2001). This approach contrasts with a conventional optimization, which seeks to maximize performance subject to some available constraints (e.g., cost). Here the intention is to help decision makers to understand the implications of alternative strategies under a range of different futures, rather than to optimize with respect to particular objectives.

Social, economic, environmental, and technological changes in the future will have profound impacts on the demand for and capacity of infrastructure services. For each of the infrastructure sectors, the authors have reviewed the factors that may influence demand for infrastructure services in future and have ranked these as primary and secondary "drivers." Commonalities across sectors were identified to develop a concise set of drivers of change. These drivers were identified through an iterative process involving a scoping study, workshops, and peer review by sector specialists. Fig. 1 summarizes the primary and secondary drivers defined for each sector. The fact that the sectors share many of the same drivers is a key source of interdependence in infrastructure performance. The FTA defines three broad driver themes of the various factors influencing performance in the infrastructure sectors: (1) socioeconomic change (comprising demographic and economic drivers); (2) environment/climate change; and (3) policy and technology options (comprising governance, policy and regulation, and technology).

As Fig. 1 indicates, key exogenous drivers common to most of the sectors are (1) population growth, (2) economic growth, and

| | Energy | Transport | Water | Wastewater | Solid waste |
|---|---|---|---|---|---|
| **SOCIO-ECONOMIC** | | | | | |
| DRIVER: Population growth | Primary | Primary | Primary | Primary | Primary |
| DRIVER: Household size | | | Primary | Secondary | |
| DRIVER: Economic growth | Primary | Primary | Secondary | | Primary |
| DRIVER: Energy costs | Primary | Primary | Primary | Primary | Secondary |
| **ENVIRONMENT / CLIMATE CHANGE** | | | | | |
| DRIVER: Mean temperature change | Secondary | | Primary | | |
| DRIVER: Change in precipitation | | | Primary | Primary | |
| **POLICY AND TECHNOLOGY OPTIONS** | | | | | |
| DRIVER: Centralized / decentralized decision making | Primary | | Secondary | | |
| DRIVER: Carbon emissions reduction targets | Primary | Secondary | Secondary | Secondary | Secondary |
| DRIVER: EU directives / National strategies and standards | Secondary | Secondary | | Primary | Primary |
| DRIVER: Improved waste processing technologies | | | Secondary | Primary | Primary |

KEY: Primary Driver; Secondary Driver

**Fig. 1.** Primary drivers by sector, including secondary drivers where relevant

(3) energy costs. Consequently, these three drivers were used to develop scenarios across all sectors (where applicable) for the FTA. An example of how these primary drivers are quantified can be seen in the following section. sector-specific issues can be as influential as these cross-cutting scenario dimensions (e.g., in regard to energy, carbon emissions targets, or in regard to water supply and wastewater, the effects from climate change on water availability and quality).

There are multiple combinations and codependencies between these different drivers. A structured sensitivity analysis would extensively sample these various sources of uncertainty. In the FTA, a simpler approach was adopted, using only three combinations of the primary drivers, representing high, medium, and low growth (Fig. 2). Although this simplified approach is less extensive in analysis of uncertainties, it provides a broad overview of the likely impacts of the more important drivers of change.

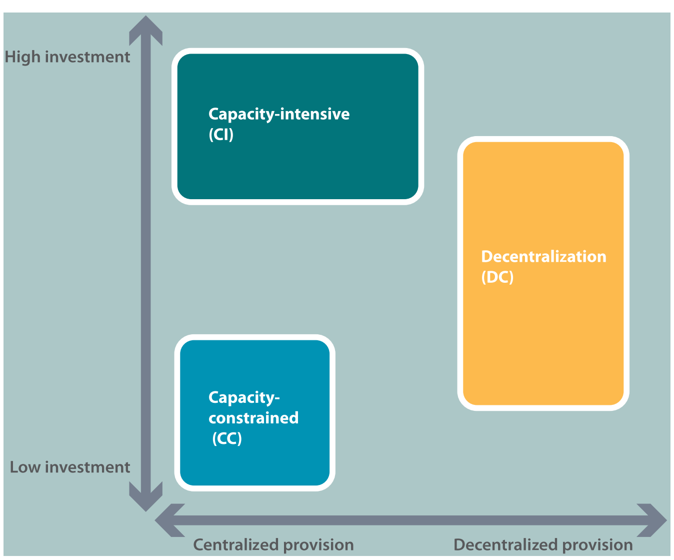


**Fig. 2.** Dimensions of the FTA transition strategies

### Constructing Long-Term Strategies for Infrastructure Provision

The aim of the FTA is to enable the evaluation strategies for regional to national infrastructure provision. A strategy is a staged program of investments or interventions in the infrastructure system. A transition to a sustainable infrastructure system is considered to be a process that leads, over a period of decades, to a system configuration (in terms of both capacity and demand) that performs well with respect to economic, social, and environmental criteria. Considering the infrastructure sectors in a strategic, integrated way, rather than in isolation, enables the exploitation of synergies and avoids unintended interactions.

The following application to Great Britain develops and explores three distinct transition strategies, defined as follows:

1. The capacity-intensive strategy represents high investment in new capacity to keep up with demand and maintain good security of supply in all sectors;
2. The capacity-constrained strategy represents low investment, in which there are no increases in the current level of infrastructure investment, but an emphasis is placed on demand management measures; and
3. The decentralized strategy represents a reorientation of infrastructure provision from centralized grid-based networks to more distributed systems. This will involve a combination of supply and demand-side measures.

The three transition strategies are analyzed against the demand for infrastructure services associated with each of the three FTA scenarios to provide insights into future infrastructure performance in a range of possible conditions. Thus, the key dimensions explored by the transition strategies are centralization-decentralization, low-high investment, and carbon constraint (e.g., environmental friendliness) (Fig. 2).

As the legacy of today's infrastructure system is a key characteristic of infrastructure, all of the strategies have as a starting point the current infrastructure systems, which limits, to some extent, the potential for radical change. After the construction of the transition strategies, the FTA is used to interpret the strategy in the context of each sector and calculate the corresponding system performance.

### Combining Scenarios and Strategies

The overall approach for conducting the FTA, making use of the scenario analysis and strategy generation processes previously outlined, is summarized in Fig. 3. The three transition strategies are analyzed in the context of each of the three sample scenarios. This analysis is conducted using simplified analyses of each infrastructure sector and the interdependencies among them. These interdependencies are modeled in terms of the demands for one sector for services from another. The sectors are arranged in a hierarchy of dependency with energy at the top, as all sectors contribute to energy demand, transport most significantly. The results are illustrated as visualizations of performance with respect to a series of performance objectives on two different time horizons (2010–2030 and 2030–2050).

The performance evaluation of the preceding three strategies across the three growth scenarios enables the exploration of the key questions in infrastructure provision. For example, the capacity-intensive strategy gives an impression of the level of infrastructure that could be provided with investment levels that are

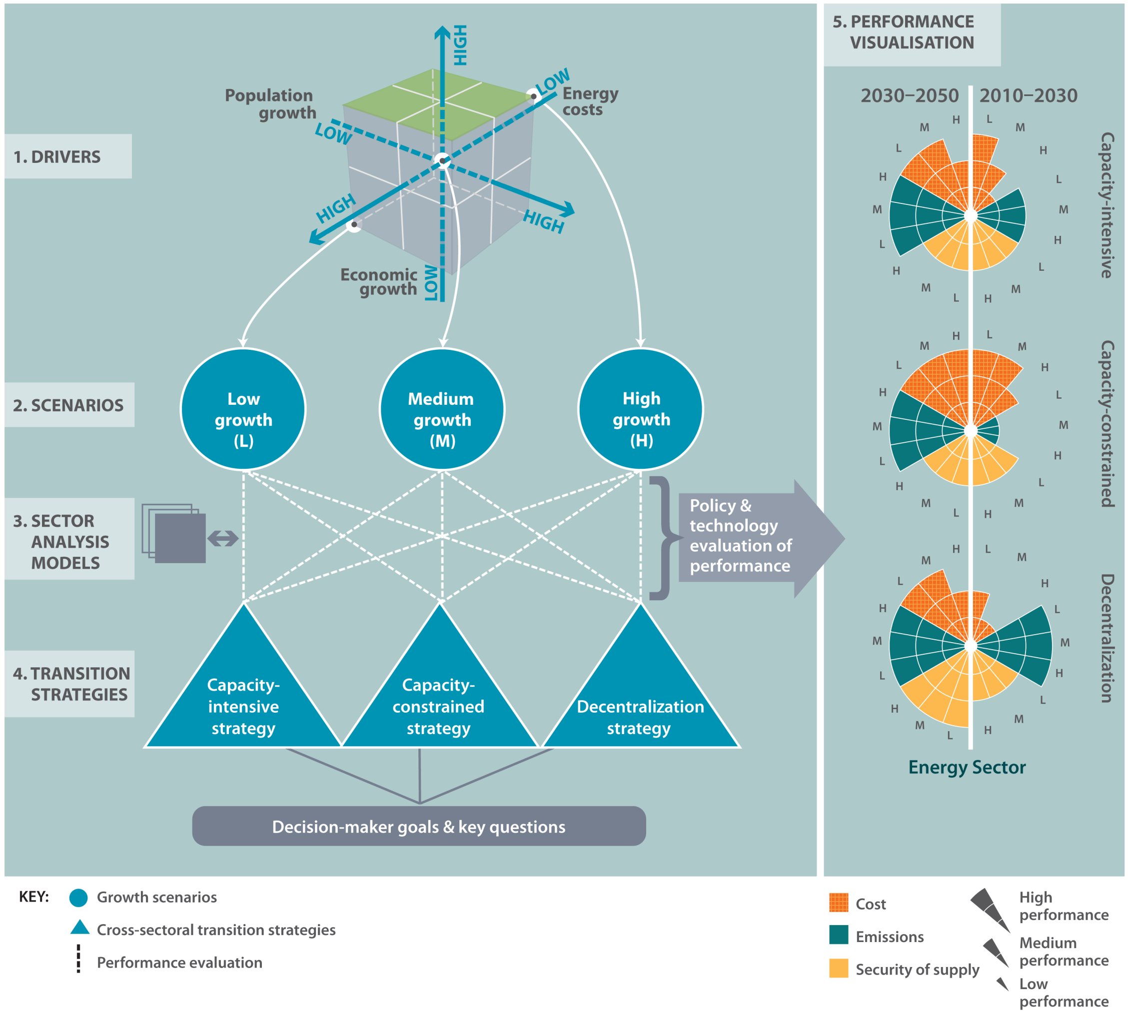


**Fig. 3.** Overview of the FTA methods and framework (adapted from Hall et al. 2013, with permission from ICE publishing)

high by historical standards. Comparing the performance of the capacity-intensive and decentralized strategies provides insight into whether accounting for local interdependence in infrastructure unlocks performance increases. Evaluating the performance over time of the decentralized strategy provides insight into the attributes and benefits (or lack thereof) of a decentralized arrangement. Evaluating the performance of the capacity-constrained strategy gives perspective on the level of service that could be provided at fairly modest levels of capital investment.

The six steps for completing the FTA are summarized as follows:

1. Identify the primary drivers that impact the future demand and capacity of infrastructure services;
2. Construct three possible futures based on these drivers extending to 2050, representing high, medium (business as usual), and low growth scenarios;
3. For each infrastructure sector, project the demand across the three scenarios;
4. Identify key performance metrics for each infrastructure sector;
5. Construct three transition strategies, which are cross-sectoral strategic plans composed of sequenced sector-specific governance and technology options. These strategies are oriented toward distinct aims and specified levels of investment; and
6. Evaluate the cross-sectoral performance (according to key metrics) of the three transition strategies across the three scenarios. Robust transition strategies perform well across the range of possible futures.

Involvement of stakeholders, who the process is designed to inform, should be integrated throughout these six steps. Each infrastructure sector already has its own planning tools and processes, which cross-sectoral analysis seeks to harmonize. The authors found ongoing stakeholder involvement was an essential step in grounding the analysis in well-trusted methods and demonstrating the utility of the results.

## Case Study: Great Britain

The nations of England, Scotland, and Wales occupy the island of Great Britain, which provides a convenient geographical boundary for this analysis. As in many advanced economies, national infrastructure in Great Britain is aging, with a considerable amount of existing infrastructure stock built in the nineteenth century (HM Treasury and Infrastructure U.K. 2011). Over the next five years, there are approximately \$395 billion of planned investments in infrastructure (HM Treasury and Infrastructure U.K. 2011). While historically the U.K. has a strong record of investment in infrastructure, in the last 30 years the investment in infrastructure as a percentage of gross domestic product (GDP) has reduced significantly (Blanc-Brude et al. 2007).

The Council for Science and Technology (CST) report on national infrastructure in the U.K. (2009) identified significant vulnerabilities, capacity limitations, and a number of national infrastructure components nearing the end of their useful life. Each year the Institution of Civil Engineering (ICE) publishes a State of the Nation report (ICE 2010) that includes a grading of infrastructure sectors in the U.K. The ICE's 2009 report on *Defending Critical Infrastructure* (ICE 2009) emphasized the need for long-term strategic planning. Further, the environment ministry's 2011 report on a *Climate Resilient Infrastructure* [Department for Environment, Food and Rural Affairs (Defra) 2011] makes significant steps towards identifying key risks and actions to prepare for the impacts of a changing climate in the U.K.

### Creating the Scenarios

Following the six major steps for completing the FTA, the primary drivers of change were identified as population growth, economic growth, and energy cost. For population, the Office of National Statistics (ONS) (2010) provides annual principal, low and high growth projections to 2033, and five-year projections up to 2083 in England, Scotland, and Wales; the expected growth level in 2083 was then extended to 2100 (Fig. 4).

In their ongoing assessment of the economic growth of emerging countries, PriceWaterhouseCoopers (PWC) give estimates of future long-term growth, based on (1) World Bank data for growth up until 2009, (2) PWC's short-term projections for the years up until 2014 and (3) their long-term growth assumptions (population growth and increases in human and physical infrastructure) for 2015–2050 (PWC 2011). The projections of GDP growth up to 2050 is 2.3% per annum, which is consistent with historic trends (Hicks and Allen 1999). To provide ranges, upper and lower boundaries of $\pm 0.7\%$ per annum were selected based on historic trends. This is interpreted as reflecting uncertainties in population growth (up to 0.3% per annum) and variations in world economic conditions that influence the British economy through changes in demand for British exports (up to 0.4% annum). Hence, the three GDP scenarios are growth from 2015 of 1.6%, 2.3%, and 3.0% per annum for low, medium, and high economic growth, respectively.

Fossil fuel price assumptions are those used by the Committee for Climate Change (CCC) (2010), from figures produced by the Department for Energy and Climate Change (DECC) (2010), based on an analysis of the international market and other forecasts. Because the baseline is 2008, these figures are for the projections published in 2009. The projections are presented in four different scenarios of future global fuel markets, but for the FTA, analyses are limited to the low (low global energy demand), central (reflecting timely investment and moderate demand) and high (reflecting high demand and producers' market power) scenarios. The resultant energy prices are

- The range for gas prices in 2030 is 0.33p to 1.15p/MJ (35 to 121p/thermo, with a central price of 0.72p/MJ (76p/thermo);
- The range for coal prices in 2030 is £32 to £83/t, with a central price of £51/t; and
- The range for oil prices in 2030 in these scenarios is $61 to $153/barrel, around a central price of $92/barrel.

These DECC projections were produced up until 2030, and CCC assumes that these costs will remain largely similar up to 2050 (Fig. 5).

The United Kingdom electricity wholesale prices are currently closely linked to national, and therefore global, gas prices as gas-fired power generation is the current long-run marginal technology. In scenarios in which electricity is decarbonized over the period to 2050, it is expected that this linkage will increasingly be broken, with electricity prices driven by the costs of low carbon technologies (renewables, fossil fuels with carbon capture and storage, and/or nuclear). Electricity costs therefore become an output of

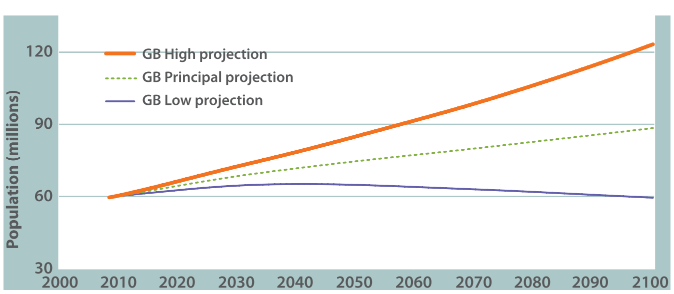


**Fig. 4.** Great Britain population projections for the FTA scenarios [data from the U.K. Office of National Statistics Population Projections (2008–2083), extended to 2100 by the authors]

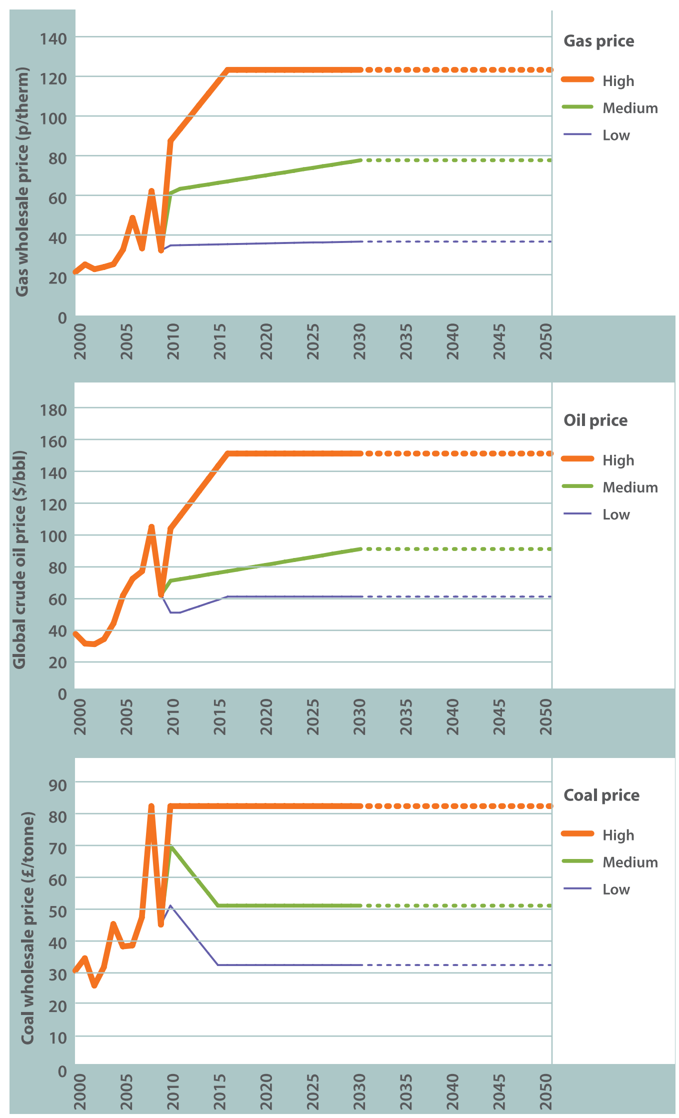


**Fig. 5.** Fossil fuel price assumptions to 2050 (data from Committee on Climate Change 2010)

**Table 1.** Summary of Fast Track Analysis Scenarios for Great Britain

| Scenario | Population growth | Economic growth | Energy costs |
|---|---|---|---|
| Low growth | Low ONS projection | Low (1.6%) | High fossil fuel prices |
| Medium growth | Principal ONS projection | Projected (2.3%) | Central fossil fuel prices |
| High growth | High ONS projection | High (3.0%) | Low fossil fuel prices |



the infrastructure system rather than an input assumption. Similarly, trends in transportation fuel prices may diverge from oil prices as alternative fuels such as electricity and biofuels become more important. In all cases the costs of fuels to distributed users are higher than those in wholesale markets because of the costs of distribution (i.e., of the relevant infrastructure). This is particularly important for gas and electricity, where final user prices exceed wholesale markets prices significantly.

These primary drivers are not independent—historically, energy costs and GDP have been negatively correlated, whereas GDP and population growth are positively correlated. These interdependencies have been incorporated in the three scenarios summarized in Table 1. The base year is 2008 for all the scenario parameters.

### *Developing Sector Models*

Models were created for each sector to project demand and evaluate the capacity provided by strategies to 2050. For the energy sector, the MARKAL model (Skea et al. 2010) was adapted for the projections and the U.K. Energy Research Centre (UKERC) Energy 2050 low carbon and low-carbon lifestyle scenarios were modified to correspond to the three FTA scenarios. Although there are critiques of the MARKAL model (e.g., it has been suggested that the model overestimates deployment of nominally cost-effective energy-efficiency technologies without proper constraints), it was selected because it provided a good representation of the complex U.K. energy system for the purposes of the FTA. As with other aspects of the FTA, the major uncertainties in the MARKAL model assumptions are assessed as far as possible through sensitivity analysis of the influential factors in energy price and demand. For transportation, an elasticity model was developed that related changes in demand to change across the three scenarios (see Fig. 6). Demand suppression was modeled using feedback relationships between demand and resulting journey times to estimate constrained demand, and any taxes or charges in strategies were also modeled (e.g., national congestion charge). Demand suppression because of congestion was modeled using feedback relationships between demand and resulting journey times. For the water sector, only public water supply was modeled by balancing the average daily volumes of public water available for use and consumers' demand for water with the population projections. Agricultural water supply accounts for only 0.8% of water abstractions in England and Wales, whereas abstractions for electicity generation (hydropower and cooling thermoelectric plant) are for the most part returned to water bodies (Defra 2008). The FTA considers each water supplier of England, Wales, and Scotland independently, aggregating available water supply capacity and demand across all company resource management zones, with results presented at a national level. For the wastewater model, the main demand driver was population, although population density and the treatment technologies implemented are key determinants of the unit cost of treatment. For solid waste, demographic projections combined with per capita waste generation were used to project waste demand for municipal solid waste (MSW), commercial and industrial (C&I), and construction and demolition (C&D), each of which responds differently to the drivers of change. This research did not address radioactive waste. Further details of the assessment models are provided in (Hall et al. 2012).

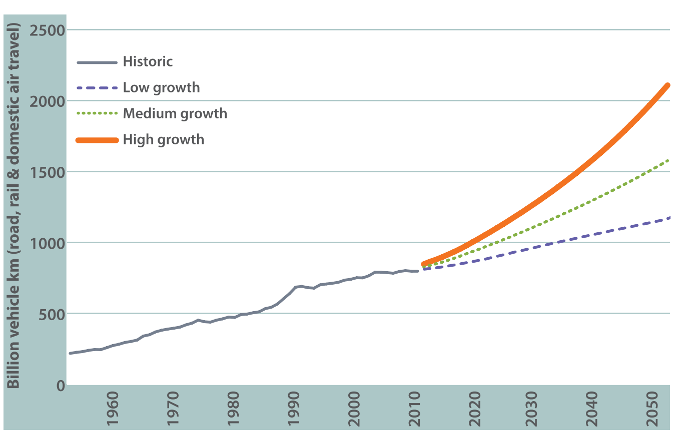


**Fig. 6.** Example of demand projections for the transportation in Great Britain across the FTA scenarios

### *Developing and Evaluating Infrastructure Transition Strategies*

The amount of infrastructure capacity that can be provided is to a great extent determined by the amount of available investment. The historical and current levels of investment in national infrastructure in Great Britain were explored to provide sensible bounds on these levels of investments. During the past five years, £150 billion was invested in infrastructure in the United Kingdom (HM Treasury and Infrastructure U.K. 2010). This represents an investment of approximately 2.1% of GDP. United Kingdom GDP data used for calculation from the International Monetary Fund's (IMF) World Economic Outlook (WEO) from 2005–2009. Over the next five years, there is an estimated £195 billion of planned investments in infrastructure (HM Treasury and Infrastructure U.K. 2010). Values from *NIP 2010* were used for the construction of the transition strategy investment levels, as the *NIP 2011* values were unavailable at the time of the analysis. Using projected U.K. GDP data for 2011–2015, this investment would represent 2.59% of GDP. United Kingdom GDP data used for calculation from the IMF's WEO from 2011–2015. Notably, this planned investment is lower than Organisation for Economic Co-operation and Development (OECD) projections of £50 billion per annum (i.e., approximately 3.32% of GDP).

These figures provide median infrastructure investment levels over the next five years at 2.5% of GDP. Hence, high and low investment levels are taken at 5% and 1.5% of GDP, respectively. These values are near to the upper (5.2%) and lower (1.5%) bounds of public investment in infrastructure for the last 40 years (Blanc-Brude et al. 2007).

To allocate investments across infrastructure sectors to constrain the options for each sector, the planned distribution (in terms of percent total investment) was used for the next five years (HM Treasury and Infrastructure U.K. 2010). These values were then translated into a percent GDP investment for each national

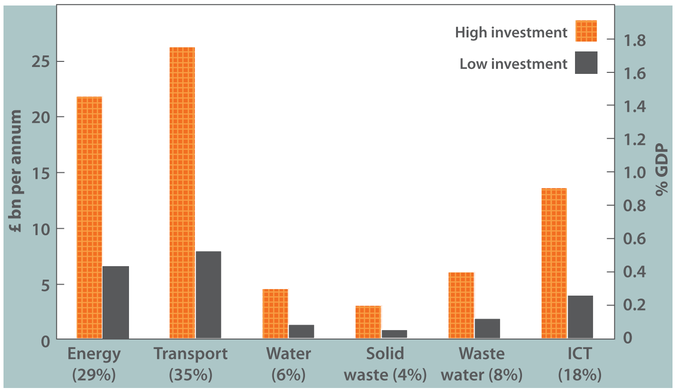


**Fig. 7.** High and low investment levels by sector as a percentage of Great Britain GDP (right axis); absolute investment by sector per annum over the next 5 years is provided for illustrative purposes, with values assuming an equal annual investment over the 5-year period (left axis); percentage of total national infrastructure investment by sector is provided in parenthesis below the sector name; proportion of water and wastewater allowed capital expenditure (Ofwat from 2010 to 2015) was used to disaggregate water and wastewater investment; all values are in 2009 prices

infrastructure sector. Fig. 7 summarizes these results and provides the average absolute annual investment value using U.K. GDP projections for the next five years for illustrative purposes. Using this information, specific portfolios of technology and policies were selected for each of the three strategies for each of the infrastructure sectors.

### *Energy Sector*

The Shannon-Wiener index was used as a metric of energy supply security (Fig. 8), according to which the decentralized strategy performs best, thanks to the diversity of supply sources. However, this index does not measure the capacity margin that is large in the capacity-intensive strategy.

In all FTA scenarios, the capacity-constrained strategy has the lowest cost attributable to an emphasis on demand reduction. The decentralized strategy scenario has the highest cost because of the use of less cost-effective technologies.

Under the FTA medium growth scenario, carbon emissions reductions of 80% across the economy can be delivered by all of the infrastructure transition strategies. Under the high growth scenario, carbon targets would inevitably be more challenging, and higher absolute levels of investment are required to ensure security, but this investment is a lower proportion of GDP. Conversely, carbon targets are less challenging under low growth, but investment requirements form a higher proportion of GDP.

### *Transportation Sector*

The low growth FTA scenario is more consistent with historical trends in transportation demand (Fig. 6). The transition strategies that were analyzed in the FTA involve differing levels of capital investment in roads and rail, including investment in the HS2 high-speed south-north rail link. Transportation infrastructure would be particularly stressed under the high growth scenario.

Vehicle emissions standards and differing rates of uptake of electric vehicles were also analyzed. Future electrification of road transportation sector would reduce emissions at the point of use, but could result in more congestion because of price effects (moving from highly taxed petrol to untaxed electricity).

The capacity-intensive strategy (high investment and fast uptake of electric vehicles) would result in higher growth in demand (e.g., 23% more car/van kilometers in 2050 compared with the reference case). Although contributing to congestion, this demand growth is compensated by improved fuel efficiency (approximately 70%), thus it results in the largest reduction in $CO_2$ emissions (19% fewer emissions from cars and vans, and 25% fewer emissions from Heavy Goods Vehicles in 2050 compared with reference case).

The capacity-constrained strategy (low investment, low uptake of electric vehicle, introduction of a national congestion charging scheme) would result in the lowest growth of demand, with an estimated reduction of car/van kilometers by 3%, and with reduced $CO_2$ emissions of 7.3% for car/vans and 2.4% for HGVs in 2050 compared with the reference case.

### *Water Supply Sector*

Contrasting levels of water demand and supply-side measures were tested in the capacity-intensive and capacity-constrained strategies using data on public water supply in England, Scotland, and Wales. Although security of supply has improved since privatization of the water industry in 1989, population growth and climate change represent a threat to the industry over the coming decades unless per capita demand is reduced and/or capacity is increased (Fig. 9). This national picture masks large regional variations across

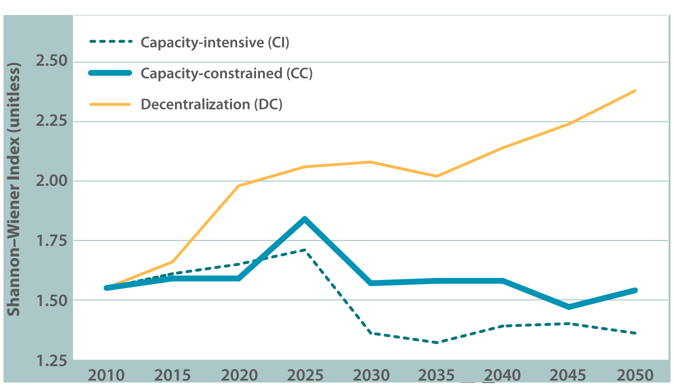


**Fig 8.** Diversity of supply options for the energy sector in Great Britain high growth scenario across the three transition strategies using the Shannon–Wiener index; higher index values denotes greater diversity of supply

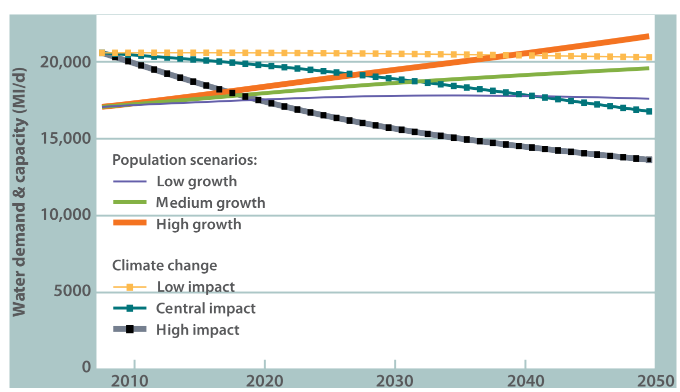


**Fig. 9.** Demand for public water supplies in Great Britain for the three population scenarios (with constant per capita demand), and the effect of the low, central, and high climate change on water availability (without the provision of additional water supplies)

Great Britain, with most challenging future conditions in the faster-growing southeast of the country. The capacity-intensive transition strategy implies high investment in supply infrastructure (including reservoirs, transfers, and desalination) as well as in capital programs of leakage reduction. These measures contribute to security of supply in terms of both capacity and flexibility of use of resources. In high climate change and population growth scenarios, the strategy sees rapidly increasing capital and energy costs. The strategy is threatened by the possibility of climate change reducing water availability, the requirements for restoring aquatic environments and the energy implications of desalination and interbasin transfers.

The decentralized strategy implies more local self-sufficiency, which is vulnerable to supply and demand side uncertainties. The capacity-constrained strategy emphasizes vigorous price and regulatory measures to reduce demand to an average of 110 L/person/day by 2050, which have the added benefit of reducing energy use in the water sector and by water consumers. At the same time, margins between supply and demand are eroded, with implications for security of supply.

### Wastewater Sector

For wastewater treatment, demand is determined by population. However, population density and the treatment technologies implemented determine the unit cost of treatment. As with water supply, economies of scale favor centralized strategies, and increasing population density further reduces costs. In the capacity-constrained strategy, for which incremental changes to current infrastructure are assumed, energy costs increase rapidly. The performance of the capacity-intensive transition strategy is characterized by replacement of existing energy-intensive treatment capacity with new treatment capacity using new energy recovery technologies. These technologies allow wastewater treatment to become an energy-neutral or energy-generating process. However, these new treatment technologies still require research and development. The cost and long design life of the existing sewerage infrastructure means that radical transitions would be very costly. This will mean managing the existing assets actively and intelligently, perhaps accelerating the adoption of the active monitoring and control of sewerage systems and developing strategies to incrementally replace or renew the network.

### Solid Waste Sector

For solid waste, in most scenarios, European Union and local government-imposed targets will require new capacity for some treatments (e.g., composting and recycling), but this could be achieved at the investment levels envisaged in any of the transition strategies. However, in the high-growth FTA scenario, it will be challenging to meet recycling targets, and the implied requirement for new treatment sites may also be problematic.

### Information and Communications Technologies

The capacity of ICT in Great Britain and globally has continued to rapidly expand, keeping well ahead of demand thanks to ongoing innovation in a competitive market. It is anticipated that this arrangement will continue, so the sector has not been subject to the same quantified analysis as other sectors. In 2010, ICT consumed an estimated 13–16% of the total electricity in the United Kingdom. Projections indicate that global electricity usage in ICT will grow by approximately 9% per year, a trend that may continue up to 2020. However, since 2000 there has been a continuing decrease in growth for home computing and other electronic consumer goods in the United Kingdom, and new products have greater energy efficiencies, which may serve to depress future growth of energy use in ICT. Beyond 2020, technological changes make electricity demand from ICT very difficult to project.

### Synthesis

Though each infrastructure sector requires a somewhat different set of metrics to evaluate its performance, performance can be reported with respect to three metrics that apply across all sectors: (1) cost, (2) $CO_2$ emissions, and (3) security of supply. Fig. 10 represents the visualization of this performance constructed by employing the FTA methodology to Great Britain. This enables the cross-sectoral evaluation of the transition strategies and evaluation of the key questions of interest to stakeholders. These are discussed in turn.

### What are the Implications of Growing Demand for Infrastructure Services?

High growth in demand for infrastructure services is associated with increasing needs and costs for infrastructure provision, in particular given the capacity-intensive and decentralized transition strategies, but high growth in demand is associated with scenarios in which more resources would be available for infrastructure investment. However, high growth in demand is also associated with higher greenhouse gas (GHG) emissions, unless the capacity-intensive transition strategy is adopted, in which case, innovation and investment enables a successful transition to infrastructure systems that are all effectively decarbonized. Higher transportation demand is associated with increased transportation congestion even given a capacity-intensive approach to transportation infrastructure provision, as without demand-management measures, demand continues to expand to fill the available capacity.

### What are the Implications of Constrained Investment in Great Britain Infrastructure Capacity?

Evaluating the performance of the capacity-constrained strategy provides insight into the implications of constraints on investment levels for infrastructure. For example, in the water sector, the capacity-constrained strategy requires vigorous price and regulatory measures over many years to achieve the per capita water demand target of 110 L/day. Security of supply is eroded, especially in high-growth scenarios. The capacity-constrained strategy is the least-cost approach, as costly supply-side measures are avoided through demand management. However, whereas demand reduction can, under some circumstances, result in efficiency improvements without deterioration in the quality of the infrastructure service (for example, improved building insulation reduces energy requirements for space heating), in other sectors, notably transport, stringent demand reduction will have implications for the economy and society.

### What are the Implications of a Carbon-Constrained Future?

As a consequence of the Climate Change Act (Great Britain 2008), the United Kingdom is committed to a reduction in GHG emissions of at least 80% (relative to 1990 levels) by 2050. The U.K.'s GHG mitigation commitments imply a major restructuring of the U.K.'s energy supply infrastructure and ripple through other infrastructure sectors, which are all dependent on energy. Changes within these sectors in turn influence the energy sector, in particular in the case of a transition to electric vehicles. For both wastewater and solid waste, there is the potential for the energy demand from these sectors to be met through conversion of the waste streams to energy.


**Fig. 10.** Infrastructure sector strategy performance for Great Britain, with respect to cost, $CO_2$ emissions, and security of supply for each transition strategy

### *What are the Implications of a Decentralized National Infrastructure System?*

The FTA revealed that reorientation towards a decentralized arrangement of infrastructure (both in terms of technology and governance) could result in infrastructure performance increases. For example, in the energy sector, the decentralized transition strategy resulted in the greatest diversification of energy supply options. Decentralization also has the potential to capitalize on interdependencies (e.g., through local waste to energy conversion or combined heat and power plants) and provide new supply options (e.g., rainwater harvesting in the built environment). However, the evaluation of the cross-sectoral performance of the decentralized transition strategy indicated that there are significant front-loaded capital investment requirements to transition towards a decentralized arrangement, particularly in the high and medium growth scenarios.

### *What are the Implications of Interdependence among Infrastructure Sectors?*

Demand for different infrastructure sectors is highly correlated, both because of the final demand associated with population and economic growth and because of intermediated demands among infrastructure sectors. The FTA has revealed the importance of cross-sectoral interdependence, in particular through energy demand from all sectors. Potential changes in demand (e.g., from electric vehicles and as a consequence of ICT) need to be accommodated in the energy sector. Changes in other sectors, for example, in transportation congestion or water availability, will also have cross-sectoral impacts. The FTA has not revealed new opportunities that could be accessed by taking interdependence into account, though these may exist at the scale of individual facilities or infrastructure corridors. However, understanding interdependence is essential to recognize new cross-sectoral demands that otherwise might not be accommodated and to minimize the risks of infrastructure failure.

## Conclusions

The development and application of the fast track assessment to Great Britain demonstrates the feasibility and utility of long-term cross-sectoral analysis of infrastructure demand and capacity on broad scales. The FTA demonstrates how different sectors are shaped by many of the same drivers, especially those that influence demand (demography, economy) and energy prices. Where new investment is required, different sectors may be competing for the same pools of public and/or private finance. A cross-sectoral approach such as the FTA provides the opportunity to define a common direction of travel and to understand the contribution that separate policies or plans make to overall performance. Further, developing and evaluating a coherent, integrated plan could serve as the basis for consistent regulation, which would serve to further attract the necessary private investments amidst the competitive global market. Additionally, it could provide finance and workload continuity, and avoid "stranded assets." Yet analysis of governance arrangements has underlined how current regulatory frameworks are not well adapted to this system of systems perspective.

The FTA was conducted in close collaboration with partners in industry and government. This provided key inputs to the methods, and review and reflection on the results, significantly improving their quality. To be successful, such stakeholder engagement needs to be planned, executed, and sustained. The FTA represents the first step in a longer-term program of collaboration and engagement that is using the insights provided to develop a more detailed national infrastructure systems of systems assessment model (Infrastructure Transitions Research Consortium 2013). The development of results from this new modeling system will be the subject of future papers.

Although aspects of the FTA have been customized for the particular context of the United Kingdom, the framework for the assessment is generic and potentially transferrable to different settings. The first application has made use of the natural geographical boundary of the island of Great Britain, though Great Britain is multiply connected to the continent of Europe, the island of Ireland, and the wider globe in energy, transport, and digital communications infrastructures. The first application of the FTA relied on the existence of data and scenario assessment capability for Great Britain, which would also be a requirement in future applications elsewhere in the world. The coherence of policy and regulatory arrangements within the assessment area (though these do differ in various ways between England, Scotland, and Wales) also contributed to the utility of the assessment. The conceptual approach is transferrable to mature industrialized economies like the United Kingdom, which have a large stock of existing infrastructure and challenges for sustainable infrastructure provision in future.

The FTA made use of established scenario analysis methodology and planning models and data sets from each infrastructure sector. The use of relatively simple sector models has enabled running of multiple scenarios and application at a national scale. The approach is novel in the application of consistent methodology and scenarios across different infrastructure sectors, including the development of strategies for infrastructure provision and infrastructure performance metrics that apply across sectors. The use of a system of systems framework has enabled consideration of the significant interdependencies among different infrastructure sectors, in the form of the demands that different infrastructures place on one another. The approach could be criticized for being "demand driven" and for its limited attention to the feedback between infrastructure capacity and demand. The authors argue, however, that a range of different scenarios of demand for infrastructure services is considered and do not necessarily guarantee that capacity will meet demand. This approach is one of exploring infrastructure performance across a range of future possibilities. Feedback is built into the modeling to some extent, for example, in the feedback between traffic congestion and transport demand, but it is acknowledged that larger-scale feedbacks, for example, between infrastructure investment and economic growth, are neglected in the assessment framework.

Having demonstrated the principles of this cross-sectoral assessment approach in the FTA, further more-detailed and ambitious research is now developing spatially disaggregated sector models. The authors consider this to be essential given the fundamentally spatial nature of infrastructure and the need to consider where investment is required. The analysis is being extended to sample much more extensively the future scenario space and to test a large set of possible strategies. Further research is also exploring methodologies for visualization of the high-dimensional spatial-temporal results.

Assessment such as the FTA can increase the confidence of decision makers that infrastructure capacity and demand can be efficiently matched while avoiding risks of failure or unforeseen side effects. Such assessments can assist in unlocking performance gains (including sustainability) by making sector-specific infrastructure plans and investments in the context of a cross-sectoral strategy. Further, by focusing on the long-term, they can assist in the prioritization of short-term and long-term investment requirements. This could serve to increase the efficient use of resources by appropriately targeting investments on key needs.

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