Tunnelling through the complexity of national infrastructure planning

New methods for strategic analysis of infrastructure systems are helping to plan the billions of investment that will be needed to sustain society's lifelines.

Infrastructure, including energy, transportation, water, waste and digital communications, is essential for human well-being and economic productivity (1). Indeed in the current economic climate governments worldwide are increasingly looking to investments in infrastructure for short-term stimulus and to enhance longer-term economic competitiveness. In many ways, infrastructure defines the boundaries of national economic productivity, and is an often-cited key ingredient for a nation's economic competiveness (2). For example, the World Economic Forum lists infrastructure as the second 'pillar' in its Global Competitiveness Index (3). Infrastructure networks are also one of mankind's most visible impacts on the environment. As infrastructure is largely made up of long-lived assets with high up-front costs, the wrong decisions during planning and design can 'locked in' unsustainable patterns of development. To steer towards more sustainable infrastructure systems requires a transformation in both thinking and methodology.

The UK Infrastructure Transitions Research Consortium is a collaborative research programme funded by the Engineering and Physical Sciences Research Council with the aim of delivering the theoretical research, models and practical decision support tools to enable strategic analysis and planning of a National Infrastructure system fit for the 21st Century.

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Over the last century, infrastructure has evolved from a series of unconnected structures to interconnected networks that can place significant demands upon one another. For example, increases in demand for water has the effect of increasing demand for energy due to the energy intensity of water treatment and distribution (e.g. pumping). The key forces that influence demand for infrastructure services are deeply uncertain in the long term. For example, changes in population and economic growth both serve to modify demand for infrastructure services. Climate change is undermining the conventional assumptions of infrastructure designers about the environmental forces to which infrastructure will be subjected (4). Still more uncertain is the role that technological change will have on patterns of behaviour and demand for infrastructure services. Yet while a 'predict and provide' approach to infrastructure planning may be out-dated, infrastructure owners still have to look far into the future and plan for a range of eventualities. Current methods and models for infrastructure planning and design are not well suited to incorporating cross-sectoral interdependencies or to coping with the major uncertainties that lie ahead. If the process of transforming infrastructure is to take place efficiently, while minimizing the associated risks, it will need to be underpinned by a long-term, cross-sectoral approach which considers a wide range of possible futures.

Thinking has already shifted from infrastructure projects to infrastructure systems. Now the challenge is broadening from the infrastructure systems in a particular sector to embrace a systems of systems approach. Systems of systems are large-scale, integrated, complex systems that can operate independently but are networked together for a common goal (5). Infrastructure fits well in this framing, as individual sectors are complex networks that rely on other sectors to provide infrastructure services.

AT A CROSSROADS

The infrastructure assets of developed countries in the west and the east are ageing and deteriorating (6), while under the pressure of ever increasing demand. Consider for example the water infrastructure in London: nearly half of the water mains are over 100 years old, yet the system is having to cope with increasing demand due to population growth. In the case of the energy sector, the UK will need to replace 25% of its electricity capacity in the next decade as it will come to the end of its life or be phased out in order to meet EU regulations for large combustion plants (7). Further, the need for the UK to increase the proportion of final energy consumption from renewable sources to 20% to meet binding EU targets (8, 9) implies a transformation of the electricity transmission grids.

Thus, highly developed countries are now at a critical crossroads where the pathways chosen for new and replacement capacity will both dictate future infrastructure supply security, and have critical implications for climate change. Yet it is in rapidly industrialising countries that the most significant infrastructure commitments are now being made, locking in future patterns of development and carbon emissions. China for example spent approximately 6.8% of GDP (10) on transportation and water infrastructure during the 2010/2009 fiscal year – over two and a half times that of the U.S (11, 12) in 2007. Now more than ever, it is essential that governments and utility providers have access to new methods that enable the evaluation of the performance and impact of long-term plans and policy for infrastructure service provision, including accounting for the complexity and large uncertainty.

A GLOBAL MOBILISATION

Although neglected over recent decades, infrastructure is now high on the national and international agenda and several research programs have formed to begin to develop new approaches to addressing the interdisciplinary challenges of infrastructure provision. For example, the Next Generation Infrastructures programme, led by the Technical University of Delft in the Netherlands has made advances using agent-based modelling and serious gaming models to help communicate the complexities of infrastructure systems. The SMART Infrastructure Facility at the University of Wollongong in Australia recently began as a major research initiative and is rapidly developing a suite of simulation models and a 'Multi-Utility Dashboard' for reporting the real-time status of infrastructure performance.

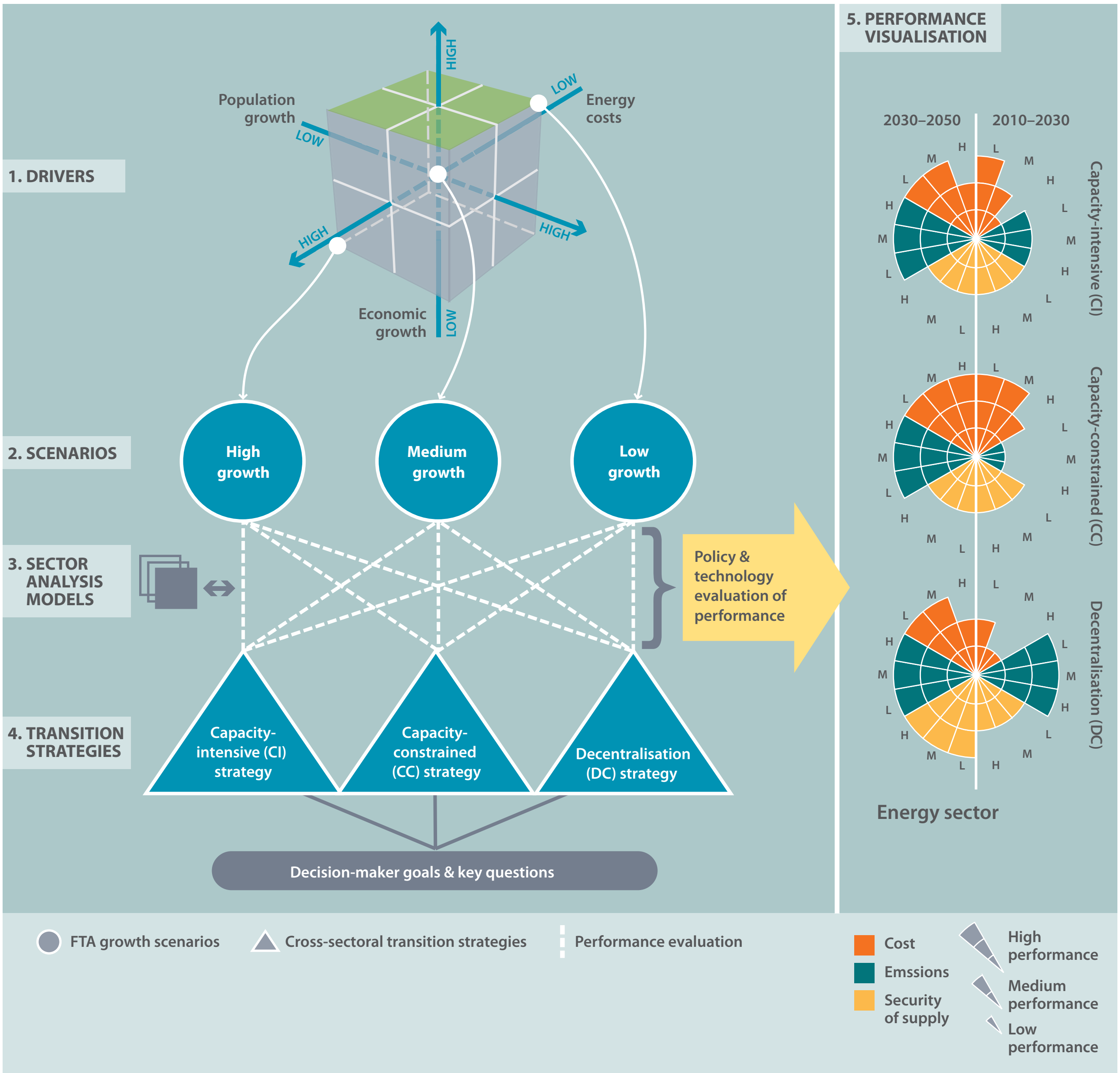
In the UK, the Infrastructure Transitions Research Consortium (ITRC) formed as a multidisciplinary collaboration of scientists, engineers, economists and policy-makers, funded by the UK's Engineering and Physical Sciences Research Council to analyse the long-term dynamics of interdependent infrastructure systems. Composed of seven universities (i.e. Oxford, Cambridge, Newcastle, Leeds, Cardiff, Southampton, and Sussex), the consortium is creating a new generation of models and tools to assist policymakers in the evaluation of strategies for infrastructure provision.

DEVELOPING A NEW ROADMAP

A blueprint for a new conceptual 'systems of systems' methodology is beginning to emerge from the work of ITRC. The methodology enables the evaluation of a wide range of long-term cross-sectoral strategies for infrastructure provision. In order to account for deep uncertainty in the long-term, the methodology incorporates a scenario analysis framework to evaluate strategies under multiple possible futures.

Analysis of strategies for infrastructure provision can be thought of in five main stages (Figure 1). The first step is to (1) identify the drivers of change, which are the primary exogenous forces that affect demand for and performance of infrastructure services over relevant timescales – at least two decades in the future, half a century for most civil infrastructures and an even longer to assess the 'lock-in' effects on land use and development. (2) To provide the context for analysis of infrastructure performance it is then necessary to create long-term future scenarios (i.e. internally consistently possible futures) from the key drivers. Next, (3) develop strategic models of the demand for and performance of each infrastructure sector.

Figure 1. An application of the methodology by the ITRC showing the four main stages of identifying the drivers of change, creating future scenarios through the variations of the key drivers, and developing, evaluating, and visualizing the performance of long-term cross-sectoral strategies for infrastructure service provision.



While strategic models exist for most infrastructure systems, but have to be adapted to operate in a consistent way at a national scale and over long assessment time-frames. This required the interaction and collaboration between sector experts and model developers.

This interaction is fundamental to systems of systems analysis. Next, (4) develop transition strategies, which are cross-sectoral long-term strategies for infrastructure service provision. They are composed of a portfolio of supply-side (i.e. capacity options) and demand management policies for each infrastructure sector oriented towards a specific aim. Recognising the inertia in the legacy of existing infrastructure, each strategy starts with today's infrastructure system, but the strategies transition into the future in contrasting policy directions. Finally, (5) identify the key common performance metrics, and evaluate each transition strategy in the context of the scenarios with respect to these metrics. This enables the identification of robust strategies (i.e. strategies that perform well in multiple possible futures (13)). In summary, the methodology creates long-term demand and capacity projections of infrastructure services over multiple possible futures, and evaluates the performance of long-term strategies for infrastructure provision.

ROAD TESTING THE METHOD IN THE UK

In the first year of intensive research, the ITRC applied the conceptual methodology outlined above to the long-term prospects for national infrastructure in the UK. The primary drivers of change across all sectors were identified as population growth, economic growth, and energy cost. Additionally, sector-specific secondary drivers were identified, and included climate change, carbon emissions targets, and environmental directives and standards. In some cases, secondary drivers were as influential as the cross-sectoral drivers.

The ITRC adapted models for each infrastructure sector and cross-sectoral demands. The ITRC methodology was piloted with only three future scenarios, each representing different settings of the primary drivers of change to 2050 (Fig. 1). Work that is now underway involves much more extensive sampling of the range of possibilities.

The pilot of the ITRC methodology tested three representative strategies to explore questions of interest to decision makers. The three transition strategies were labelled:

- capacity-intensive, providing high investment in new capacity to keep up with demand and maintain good security of supply in all sectors;
- capacity-constrained, a low investment strategy with no increases in the current level of infrastructure investment, and an emphasis is placed upon demand management measures;
- decentralised, a reorientation of infrastructure provision from centralised grid-based networks to more distributed systems, involving a combination of supply and demand-side measures.

The ITRC evaluated the performance of the strategies according to the common metrics of cost, emissions, and security of supply, along with other sector-specific metrics. Infrastructure performance in the three scenarios was evaluated over the near (2010-2030) and longer (2030–2050) term.

The results have revealed the limitations of demand management, and the benefits of diversity of supply that decentralised infrastructure can yield. The analysis has provided the evidence to 'future-proof' investments by testing their performance in the longer term.

Such methods will enable a new planning paradigm that shifts to the long-term, helping to steer towards sustainable outcomes and navigate away from undesirable side-effects. The first year of ITRC research also demonstrated that multidisciplinary collaborations between scientists, engineers, economists and policy-makers must become commonplace in infrastructure analysis and planning. The emphasis of co-production with key stakeholders was essential and interwoven throughout both the model development and review of model outputs.

THE WAY AHEAD

It would be hubristic, and misunderstanding the nature of the complex adaptive systems involved, to suppose that it is possible, decades in advance, to design a system as complex as the civil infrastructure for a technologically advanced society, and specify a strategy for phased implementation. There are too many unexpected contingencies and opportunities that may materialize in the intervening years. Predicting future technologies in a period when they are rapidly evolving is not possible. Yet on the other hand it is clear that sophisticated systems that service society do not arise spontaneously. They require sustained and strategic intent. This is a long term program – moments of maximum leverage, when opportunities in multiple sub-systems coincide, do not occur all that often – unless we plan to make them happen they may not occur at all. The pathways for reaching sustainable endpoints from the current system state therefore need to be set out now. This in turn will require further development of tools for design, appraisal and communication of alternative strategies and new modes of collaborative research.

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