National infrastructure assessment: Analysis of options for infrastructure provision in Great Britain

Interim results, January 2014

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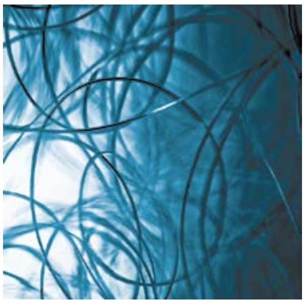
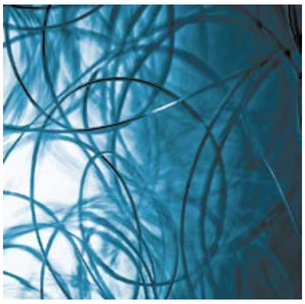


Contents



Summary

Britain's infrastructure has come into existence over many decades. We owe a considerable debt to the legacy left by the Victorian builders of railways, reservoirs and sewers. These ageing systems face considerable challenges in the future to serve a globalised economy. Moreover, Britain is committed to an 80% reduction in greenhouse gas emissions by 2050, which implies a transformation of energy supply, with knock-on effects that ripple through all infrastructure sectors.

In the face of these challenges, there have been many calls for a longer term and more strategic approach to infrastructure provision in Great Britain. Decisions about infrastructure are long term commitments: wrong choices now could lead to future failures, and/or lock-in for future generations to inappropriate infrastructure systems, with high debts and maintenance costs and could also have important implications for sustainability. Thus we need a long term approach to analysing the options for national infrastructure provision across a wide range of plausible futures. That, however, is a complex technical task – much easier said than done. It involves understanding the drivers of demand for infrastructure services in the future and the ways in which the different infrastructure networks might cope with, and respond to that demand. The aim of the Infrastructure Transitions Research Consortium (ITRC) programme is to deliver that modelling capability for the UK.

The ITRC has now developed an integrated system-of-systems model (NISMOD) that can simulate the long term performance of infrastructure networks in Great Britain. This analysis capability has been used to compare alternative long term strategies for infrastructure provision. In total we have examined 17 different options for infrastructure provision, to be implemented over the coming decades, under a wide range of scenarios of future demographic change, economic growth and climate change. This report presents interim results from that new analysis, helping to evaluate and compare alternative strategies for national infrastructure provision. Importantly, for the first time this report demonstrates how long term, cross-sectoral plans for infrastructure provision at a national scale can be mapped out and analysed. This analysis is based on the examination and comparison of four alternative strategy portfolios for infrastructure provision:

- **Minimum Intervention (P-MI)**, which reflects historical levels of investment, continued maintenance and incremental change in the performance of the current system.
- **Long-term Capacity Expansion (P-CE)**, which focuses on large scale, long-term investment into physical capacity expansion to meet increasing demand.
- **Increasing System Efficiency (P-SE)**, which focuses on deploying the wide range of technological and policy interventions to increase efficiency of the current system,

targeting demand for infrastructure services as well as the capacity of infrastructure systems.

- **New Services and Planning (P-NS)**, which focuses on restructuring the current mode of infrastructure service provision through long-term investment in innovation and design of new service delivery models. A combination of targeted centralisation and decentralisation approaches are deployed.

Which of these strategies, or combination thereof, is adopted will be a matter for political, economic and societal choice. The ITRC is providing the evidence to explore the implications of those choices and to inform the development of a strategy for national infrastructure provision that looks to the long term, taking into account interdependencies and uncertainties. We find the following:

- **Population** is a key driver of demand for infrastructure services in future. Our analysis is based on Office of National Statistics projections but at a higher spatial resolution, with a central projection of British population in 2050 of 75 million and a range of 65–95 million.

- Our **macro-economic modelling** projects UK GDP in the range £2.7–3.7 trillion by 2050. We have explored a range of projections for the structure of the UK economy and patterns of employment, though in all cases **London and the surrounding regions continue to dominate**, with a corresponding requirement for infrastructure services in this part of Britain.

- Based on current rates of **demand** for infrastructure services, our population projections could translate into a corresponding increase in demand for energy, water and waste disposal. We have used a new model of energy demand to explore the technological and behavioural changes that may modify demand. **Implementation of ambitious efficiency measures** and **local generation** of electricity from photovoltaics and **combined heat and power** could bring electricity demand on the grid down by ~5% in 2050 (i.e. 355TWh less electricity demand relative to 2010) and gas demand down by ~50% in 2050 (i.e. 260TWh less gas demand relative to 2010). However, steps to **electrify heat and transport** would significantly increase electricity demand by 83% in 2050 (relative to 2010), whilst further reducing demand for gas and liquid fuels.

- We have explored strategies for **electricity supply** that incorporate varying components of nuclear, renewables, gas (CCGT) and coal (with or without carbon capture and storage). The capacity of CCGTs in 2050 is high in all strategies. CCGT capital costs are lower than coal plant, and therefore always more economic at low load factors. In strategies where there is a carbon price floor (currently £16/tCO_2 rising to £30/tCO_2 by 2020), coal plants are also relatively expensive to operate. CCGT capacity in the high nuclear and offshore strategies is exceptionally high. This is to deal with inflexible (nuclear) and variable (wind, wave etc.) generation and to meet peak demand.

- Between 7 and 18GW of additional **electricity transmission capacity** will be required by 2050, mostly due to connection of offshore wind in Scotland and offshore wind in north east and west England. Further exploitation of offshore wind will require even more investment in transmission capacity in the period 2020–2050, with our model projecting an additional ~65GW of electricity transmission capacity required by 2050 in the case of high investment in offshore wind.

- **LNG import capacity** is currently 141Mm3/day. A Minimum Intervention (P-MI) approach with high gas dependence could require a doubling of that capacity together with a construction of a new **interconnector pipeline**. Some additional LNG capacity will be required even if high proportions of nuclear supply are adopted.

- Estimates of required **investment in energy supply and transmission infrastructure** range from £433–570 billion by 2050 (cumulative costs discounted to 2010), with the exception of a strategy that involves a high component of offshore wind, which is projected to cost in excess of £1 trillion. The lowest carbon emissions will be achieved by a strategy based on a high proportion of nuclear generation.

- Projections of growth in **demand for road transport** are subject to considerable uncertainties. In all of the strategies tested, the road network approaches saturation, which ultimately limits demand. It is possible that peak demand effects may cause trip rate reductions due to demographic and economic change such as younger adults moving towards cities and older adults moving out, or saturation of growth in female driving license holding and car ownership. Congestion on the road network will be concentrated in the southeast of England.

- **Electric vehicles** (plug-in hybrid or battery) could consume 81.5TWh of electricity, representing ~12% of electricity demand by 2050. Grid carbon intensity has to drop to around 100g/kWh from a current ~500g/kWh to gain the carbon reduction benefits of large scale deployment of electric vehicles. Electric vehicles could contribute to balancing the grid in the context of a high penetration of intermittent renewable.

- Without significant further infrastructure investment we predict heavy congestion along the southern end of the West Coast Main Line corridor of the **rail network**, and on links radiating from Greater London, as well as in the area around Cardiff and Central Scotland. DfT's estimates of 36–46% increase in rail passenger miles by 2030 correspond with our low to central projections.

- Without further capacity expansion, we project Heathrow, Gatwick and Luton **airports** becoming full up within the next decade, but other airports such as Teesside and Inverness retaining spare capacity in all the foreseeable futures.

- Requirements for investment in municipal **water supply** is a function of population, per capita demand, the effects of climate change on water availability, and the changing regulation of water abstractions. Increased effort could reduce demand from the current average of 150l per person per day to 110l per person per day. Nonetheless, we project requirements for investment in water supply infrastructure, though with considerable regional variation.

- Currently 40% of freshwater abstractions in England and Wales are from the electricity sector (i.e. both hydroelectric power and power station cooling). Hydrological variability poses a risk to electricity generation that is dependent on water, so power plants (both hydro and thermo-electric) are usually situated on bodies of water with reliable yields. We project steady or **decreasing freshwater abstraction for all energy strategies** other than those with high penetration of **carbon capture and storage**, which could add ~140,000 Ml/year to freshwater abstractions (of which 110,000 Ml/year would be consumptive), 70% of which in the north of England.

- Demand for **waste water treatment** is a direct function of population. Where investment is required to keep pace with this increasing demand and replace ageing plant, current technologies imply a tendency to **further centralise treatment facilities** in order to reduce operating costs. We project a requirement for an additional £2–15billion in cumulative capital investment in waste water treatment by 2050.

- The UK **solid waste** sector deals with approximately 300 million tonnes of waste annually. In the last decade, the sector has transformed rapidly, responding to EU and national legislation. This has increased the amount of waste recycled, composted or reused and nearly halved waste going to landfill. Historically, economic growth and household waste generation were coupled, but there is some evidence that this may no longer be true, which means that the lower end of our projections involves minimal requirement for new investment in additional capacity. However, if this is not the case there will be a shortfall of between 6 and 53 million tonnes of residual municipal solid waste treatment capacity (i.e. incineration and other thermal treatment) by 2050 in England alone.

- Given the rate of technological change, we have not been able to analyse requirements for digital communications infrastructure as far into the future as in other sectors. Currently more than 73% of UK populations have access to the **internet**. The availability and increased penetration of super-fast broadband infrastructure by 2024 has been estimated to save 2.3 billion kms in annual commuting, 5.3 billion kms in annual business travel and 1billion kWh of electricity usage.

- The UK has more than 82.7 million **mobile phone** subscriptions (94% of adults). Ofcom's targets say that 4G must reach 98% of the population and 95% of the country by the end of 2017. Based on current trends and an analysis of devices and user mobility, demand for **mobile broadband** may grow between 23x and 297x over the period 2012–2030, with 80x being the mid case scenario. Capacity enhancement in mobile broadband will need to feature new technological innovations in spectrum efficiency (including via LTE-Advanced and its evolutions) at existing cell sites, as well as the inclusion of additional antennas in both base stations and mobile devices.

- There are important differences in cumulative **investment requirements** for the analysed infrastructure portfolios, with a range of £560 billion to £1.6 trillion by 2050 for Minimum Intervention and Capacity Expansion respectively. Cumulative investment for Increasing Systems Efficiency is £765 billion and New Services and Planning reaches £1.2 trillion. **Investment is dominated by energy supply except in Capacity Expansion where massive investments are made in transport infrastructure**, resulting in high levels of carbon emissions.

- **In 2050 the best environmental performing portfolio is New Services and Planning** with per annum emissions of 110 $MtCO_2$ compared to 400 $MtCO_2$ for the Minimum Intervention (based on energy supply, transport, water supply). While performance gains are made over the medium term, by 2050 only Increasing Systems Efficiency and New Services and Planning appear to be robust against long-term rising population growth trends.

- We have identified significant **interdependencies between infrastructure sectors**. Each sector is subject, to varying extents, to the same drivers of population and economic growth and energy costs. We have identified particularly strong interdependencies between **electricity supply and electric vehicles**, between **water supply and power plant cooling**, and between **digital communications and transport demand**. Our analysis of governance identifies ways in which barriers to more infrastructure co-ordination could be identified and tackled.

- Our case study of water-electricity **governance interactions** shows that in some cases co-ordination has been lacking and that there can be contradictory incentives for infrastructure providers from different sector regulators. To address this issue, we make the case for an integrated approach to governing infrastructure interdependencies. This would bring together the current primary focus on security and vulnerability concerns with more proactive incentives for coordination within and between infrastructure sectors.

The ITRC analysis of national infrastructure systems continues. A book with more complete description of the methodology and results reported here will be published by Cambridge University Press in 2014. In addition, further research to improve the NISMOD model and its application to Britain's national infrastructure is planned for 2014/15, thanks to support from the Engineering and Physical Sciences Research Council.

1 Taking the long view

The fundamental importance of National Infrastructure to societal wealth and well-being is increasingly recognised. Efficiently delivering infrastructure services to society requires a long-term strategic perspective of needs, opportunities and risks across all the infrastructure sectors.

1.1 GLOBAL SIGNIFICANCE

National Infrastructure (NI) provides the foundation for economic productivity and human wellbeing, and is the cornerstone of modern industrialised society. NI provides the energy and water resources that all societies need in order to function, and enables people, information, and goods to move efficiently and safely. Further, NI shapes the interactions between human civilisation and the natural environment. Whilst infrastructure is humanity's most visible impact upon the environment, modern sustainable infrastructure is also essential to minimising human impacts on the environment.

Various definitions of NI exist. The ITRC has been addressing critical physical infrastructure networks, namely five economic infrastructure sectors: (1) energy, (2) transport, (3) water, (4) waste, and (5) information and communication technology (ICT). The ITRC has a particular focus upon the interdependency between these five networks.

The provision of resilient, effective NI systems has become a policy focus for advanced as well as emerging economies. But NI systems face a number of serious challenges: (i) an increased demand for infrastructure services from a growing and ageing population; (ii) significant investment requirements to counter the vulnerabilities, capacity limitations and supply insecurities associated with an ageing infrastructure system; (iii) the increasing complexity, diversification and interdependence of infrastructure networks; and (iv) a widespread desire to maintain and improve environmental standards, including decarbonisation across infrastructure sectors. These challenges threaten the ability of NI to continue to provide the essential services that support nearly all aspects of daily life in advanced societies.

1.2 GROWTH AND COMPETITIVENESS

Investments for a reliable and resilient NI facilitate economic competiveness and positively impact growth (Aschauer, 1989; Munnel, 1992; Gramlich, 1994; CST, 2009). In many ways, infrastructure defines the boundaries of national economic productivity. It is often cited as a key ingredient for a nation's economic competiveness (Urban Land Institute and Ernst and Young, 2011). The World Economic Forum (WEF) for example lists infrastructure as the second 'pillar' in its Global Competitiveness Index, a measure of national competitiveness (WEF, 2011, 2012, 2013). Investments in increasing the resilience of infrastructure against the impacts of climate variability and climate change can serve as a competitive international advantage. Public investments in infrastructure generally have a positive impact on economic growth, and there is a strong positive relationship between the growth rates of public capital and GDP.

Infrastructure in Great Britain is often ageing, with a considerable amount of existing infrastructure stock built in the 19th century or early 20th century (HM Treasury and Infrastructure UK, 2010a): this can cause supply insecurities. Consider for example the 31,000 km of water mains in London, where nearly half (44%) are over 100 years old. Thames Water has replaced over 2000 km of London's mains since 2003, at a cost of £650 million, reducing leakage by 27% (Thames Water, 2011). In the case of transport, the last 15 years has seen growing demand across all modes of travel for long distance trips (over 160 km). This growth is expected to continue, with the Department for Transport (DfT) forecasting that between 2008 and 2043, there will be an increase of 36% in the total number of long distance road, rail, and air trips per person (DfT, 2011). In the case of ICT, the infrastructure is new, but change in demand is dramatic. Households with access to the internet increased 16% over the last 4 years (ONS, 2011), while the absolute number of adults accessing the internet every day nearly doubled from 2006 to 2010 (ONS, 2010a).

Significant levels of investment are needed to address the challenges of ageing infrastructure, growing demand, and climate change. Whilst historically the UK has a strong record of investment in infrastructure, the record of the past several decades is less good, with uncoordinated, incremental, and inefficient investments (HM Treasury and Infrastructure UK, 2010a). HM Treasury and Infrastructure UK (2011) estimated that infrastructure investment would increase significantly from £113 billion in 2005–2010 to £250 billion from 2011–2015, with further significant investment thereafter.

Maintaining and strengthening NI standards designed to protect and improve environmental quality implies an on-going programme of investment. In the European Union (EU) for example, the 1988 Large Combustion Plant Directive (LCPD) introduced measures to reduce acidification, ground level ozone and air quality by controlling emissions of sulphur dioxide (SO2), nitrogen oxides (NOx) and dust (particulate matter (PM)) from large combustion plants (LCPs) in power stations, petroleum refineries and other facilities with a thermal capacity of 50 megawatts (MW) or more (Hall *et al*., 2012). In practice this led to the closure of much of the UK's coal-fired electricity generating capacity over the last few years. The UK's own climate change and greenhouse gas emission goals will require even more radical changes in power generation technology going forward (Committee on Climate Change, 2010) and raise serious questions for the future of the natural gas energy system.

There is significant need for private investment into national infrastructure around the world. In order to attract these investments in an increasingly competitive global economy, it is essential to have coherent long-term goals for infrastructure and a policy and regulatory framework sufficiently stable for infrastructure providers to take investment and operational decisions consistent with these goals. This framework needs to include co-ordination mechanisms to ensure that different policy objectives are taken into account (e.g. energy security, affordability and sustainability) and that interactions between infrastructure sectors are considered. It also needs to include appropriate mechanisms for learning from both successes and failures (NAO, 2013). However, there are particular challenges with this long term approach, for example, risk-conscious investors could be discouraged from investing in infrastructure associated with a low-carbon economy (i.e. green infrastructure), since the economic viability of such investments relies heavily on long term policies. Policy frameworks such as the Climate Change Act are seeking to deal with such challenges – but as has been the case recently, shorter term disagreements within government about policy priorities can still have a detrimental impact on the investment climate. Further, investments in technologies such as offshore wind are considered higher risk as these infrastructure assets lack a credible investment performance track record in most countries, reflecting that there is a lot of learning and rapid technical change occurring, and developers have been historically over optimistic about costs and performance. This can often serve to discourage investors (Hall *et al*., 2012).

1.3 RISK AND INTERDEPENDENCY

Infrastructure interdependencies introduce layers of complexity, uncertainty, and risk to NI planning and design. Over the last 50 years, infrastructure has shifted from unconnected independent systems to interconnected national networks (CST, 2009). This shift has important implications for the resilience of infrastructure sectors. For example, a power failure in 2011 at a major exchange in Birmingham resulted in the temporary loss of broadband service for hundreds of thousands of customers across the UK, particularly affecting business customers (BBC, 2011). Even small, temporary failures can have significant effects on economic productivity. In the long term, these risks intensify as systems become larger and increasingly interdependent. The combined effect of ageing infrastructure, growing demand (nearing capacity limits) from social and economic pressures, interconnectivity, and complexity leads to systematic weakening of the resilience of infrastructure systems (CST, 2009). Climate related extremes have also caused major service interruptions in recent years (e.g. floods and major snowfall). Climate change is increasing the risk of extreme events (IPCC, 2012) and hence infrastructure failures.

The ITRC has been analysing the risks of infrastructure failure in Britain and the ways in which interdependency may exacerbate these risks. We have identified 'hotspots' of critical infrastructure vulnerability, which take interdependency into account. This work is not reported here. The focus of this report is to explore the interdependency in demand between infrastructure sectors, which is particular significant between electricity supply and electric vehicles, between water supply and power plant cooling, and between digital communications and transport demand.

The changing patterns of demand also influence different infrastructure sectors in rather similar ways, providing a further source of interdependence in the long term. In the UK for example, if it is possible to reduce domestic demand for water this will have implications not only for water supply, but also for energy (as 18% of household energy is used for heating water (DECC, 2011)) and wastewater treatment. Moreover, in some instances one infrastructure sector is a major component of demand for another sector: the transport sector represents 34% of energy demand in the UK, whilst electricity generation is responsible for 32% of all non-tidal water abstractions (Defra, 2009).

1.4 PLANNING FOR UNCERTAINTY

Overcoming these multiple challenges requires a long-term strategic view on infrastructure provision, especially given the long lifespan (many decades or longer) of many physical infrastructure assets (particularly in water, transport and energy), and the long lead-time to effect change in these systems (ICE 2009, ICE 2010, Hall *et al*. 2013a, Hall *et al*. 2013b). However, the feasibility of such planning for the long-term is, in turn, challenged by future uncertainties associated with demographic, economic and environmental changes, as well as uncertainties about the nature of technological change, all of which are likely to have an effect on the demands and requirements of NI systems.

In addition, there are uncertainties about the approach to governance arrangements for infrastructure that influences decision making by infrastructure providers. It is essential to take a long term view in planning for the replacement of infrastructure nearing the end of its life, and for the additional capacity that is required to meet increasing demands (HM Treasury and Infrastructure UK, 2010b).

Whilst a long term view helps ensure new NI will meet current and future demand, anticipating future demand is challenging due to the high degree of uncertainty in the long term (HM Treasury and Infrastructure UK, 2010b). Moreover, infrastructure provision can encourage patterns of development and land use that become practically irreversible. Choices about technologies can lock in patterns of behaviour and economic activity. Complex interdependencies between infrastructure sectors can intensify uncertainty in the long term planning of infrastructure. Hence, when predicting future demand for a given infrastructure sector, the demands from other sectors must be considered (e.g. the need for transportation services to provide fuel sources to the energy sector, or the necessity for energy supply to the ICT sector). Thus, evaluating the demand for a given sector in the long term requires a coordinated planning effort across infrastructure sectors to balance these dependencies.

1.5 BUILDING ON THE ITRC FAST TRACK ANALYSIS

In January 2012, the ITRC published a 'Fast Track Analysis of strategies for infrastructure provision in the UK' (Hall *et al*. 2012). The FTA was the ITRC's first national assessment of infrastructure provision. It was based on existing models and evidence, unlike the current assessment which makes use of the NISMOD system.

The FTA established important principles for national infrastructure assessment, which this study builds upon. In the FTA, three distinct cross-sectoral transition strategies were developed and analysed: two which focused on the availability of investment ("Capacity-Intensive", which assumed high investment in new capacity to maintain supply security, and "Capacity-Constrained", in which no increases to current levels of infrastructure investment were envisaged) and one based on a reorientation of infrastructure provision (the "Decentralised" strategy) (Hall *et al*. 2012). The strategies presented in this second assessment are an evolution of these three approaches explored in the FTA.

The most significant development beyond the FTA is the breadth and depth of model-based analysis at a sector level, which provides, for the first time, quantitative projections of infrastructure performance in a range of future scenarios.

1.6 OBJECTIVES AND STRUCTURE OF ASSESSMENT

The UK Infrastructure Transitions Research Consortium (ITRC) is developing models and methodology for strategic assessment of Britain's national infrastructure systems. It is seeking to analyse the choices required to ensure a competitive and sustainable infrastructure network in the long term. In support of this aim, the ITRC has developed a National Infrastructure System Model (NISMOD). This new generation of simulation models and tools provides a systems-of-systems methodological framework capable of assessing sectoral interdependencies, future risk and resilience, and total system performance.

The ITRC is using NISMOD to analyse Policy Portfolios, which are a combination of cross sector strategies that assess the long-term total performance of the national infrastructure system. This assessment is guided by the following key research questions:

- What are the different spatial and temporal trends and impacts from growing demand for infrastructure services?
- What are the policy and investment trade-offs between increasing long-term capacity to meet future demand, while limiting environmental impacts, and meeting climate change goals?
- What combination of supply and demand-side measures can be deployed for each sector that increases systems efficiency, and leverages the potential of new services and planning?
- What cross-sector strategies can be implemented that account for increasing systemic risk, uncertainty, and sectoral interdependency, while assessing total system performance?

This summary report provides the latest results from the NISMOD analysis of policy portfolios. It is structured as follows:

- Chapter 1 highlights the need for a long term perspective on NI planning in the face of emerging challenges.
- Chapter 2 provides an overview of the National Infrastructure System Model (NISMOD) framework and cross-sectoral approach using strategies and scenarios for national infrastructure assessment.
- Chapter 3 describes the ITRC's scenario analysis of the drivers and trends in demand for infrastructure services.
- Chapter 4 provides assessment results for energy, transport, water, waste and ICT sectors.
- Chapter 5 presents a cross-sector analysis of key interdependencies focusing on energy and transport, energy and water, and assessment of Policy Portfolios for long term national infrastructure provision.
- Chapter 6 explores how a more integrated approach to national infrastructure provision may be governed, regulated and delivered.
- Chapter 7 looks at next steps in the UK Infrastructure Transitions Research Consortium's model development and analysis.

Analysing the system

Traditionally, planning of infrastructure has taken place in silos, focussing on one infrastructure sector or project. A new approach is required that deals with interdependencies between sectors in the long term. The ITRC has developed an analysis framework and National Infrastructure Model (NISMOD) for national assessment of infrastructure performance.

2.1 A NEW PARADIGM IN INFRASTRUCTURE PLANNING

Historically, policies and decisions regarding individual infrastructure sectors have been made in isolation with little regard for other interconnected infrastructures. Levels of investment in infrastructure have been influenced by the perceived political and economic importance of individual sectors, and such investments have fluctuated over time (Helm *et al*. 2009, Marshall 2010). Infrastructure UK has been specifically created with the aim of ensuring a more harmonised and integrated long-term vision of national infrastructure. This is promoted through the development of a National Infrastructure Plan, which identifies a strategy for meeting the country's infrastructure needs (HM Treasury and Infrastructure UK 2010a, 2011, 2012). This highlights the increasing importance for taking a long term, and cross sectoral view of infrastructure provision, including how future investment strategies will interact between sectors.

The ITRC has developed a process to appraise the long-term performance of infrastructure policy. This starts with asking high level questions including: How much are we prepared to invest from public and private sources? How committed are we to environmental objectives? To what extent are we willing to reduce demand for infrastructure services through price mechanisms, technology, land use changes and changes in behaviour? On what timescales should we plan for? Commitments to economic and environmental policy objectives will determine how much room there is to manoeuvre in devising long term pathways for transforming the provision and use of infrastructure services.

Long term strategic analysis requires data and models to appraise options and evaluate system performance under a range of possible future conditions. Simulation modelling provides the ability to analyse in a virtual environment the long term performance of infrastructure investment strategies across a wide range of possible futures. This can provide insight and evidence concerning benefits and costs, and help safeguard against future risk and systems failure. The ITRC has developed national assessment and modelling capability to address this challenge, with the National Infrastructure System Model (NISMOD).

2.2 SYSTEMS–OF–SYSTEMS MODELLING FRAMEWORK

ITRC's modelling framework for National Infrastructure (NI) is represented as a system of systems by capacity and demand models for five different infrastructure sectors – Energy, Transport, Water supply, Waste water, and Solid waste. The aim is to inform decisions for planning by evaluating the performance of different strategies for providing infrastructure services under a wide range of future conditions. The National Infrastructure System Model (NISMOD) family is a series of models and supporting database and visualisation tools including:

- NISMOD-LP: A national model of the long term performance of interdependent infrastructure systems.
- NISMOD-RV: A national model of risks and vulnerability in national infrastructure systems.
- NISMOD-RD: A model of regional development and how it adapts to infrastructure provision.
- NISMOD-DB: A national database of infrastructure networks, demand and performance.

This report describes the use of NISMOD-LP (supported by data held in NISMOD-DB) to analyse the performance of long term strategies for infrastructure provision. The framework incorporates the following steps:

1. Generation of ensembles of future scenarios (i.e. plausible situations) of socio-economic and environmental conditions;
2. Generation of a range of interesting, distinct and plausible strategies of future NI provision;
3. Simulation of future demand and capacity in a suite of soft-coupled single sector simulation models, linked to a central infrastructure database (NISMOD-DB); and
4. Evaluation of infrastructure service performance and the uncertainty analysis or robustness of performance of the varying NI strategies across the scenario space, including interdependencies between sectors.

2.2.1 SCENARIO GENERATION

Exogenous changes to the national infrastructure system are represented by scenarios of socio-economic, climate, and technological variables that are outside the influence of national policy. The framework represents a feed-forward simulation model approach, which addresses uncertainty about these future external conditions and parameters via an ensemble approach. We have developed an ensemble of scenarios that capture exogenous variables external to infrastructure systems but nonetheless influence their performance. These include:

- *Demographic change* – affects demand for infrastructure services. The Office of National Statistics (ONS) publishes projections of population change across a range of timeframes (ONS, 2010b), and we have produced a range of possible future trajectories based on this ONS data, but at higher spatial resolution.
- *Economic change* – affects the demand for infrastructure services, both in final household demand and industrial sectors.

- *Global fossil-fuel costs* – affects both operating costs and transport costs in particular. Some national policy measures may affect these costs, but for ITRC, these are assumed to be exogenous to the models. These costs are outputs of our econometrics model.
- *Environmental change* – climate change affects resource for water and demand for energy. Scenarios of future UK climate are based upon the UKCP09 climate projections.

These scenarios provide direct data inputs for each sector model ensuring consistent assumptions are used for each sector. Section 3 describes the population and macroeconomic models and scenario results used in this assessment.

2.2.2 STRATEGY GENERATION

There are many possible strategies for the provision of future infrastructure services. Strategies may combine measures to increase the structure or capacity of national infrastructure networks and manage demand. Supply and demand-side measures are becoming increasingly integrated for example through development of smart grid networks. In ITRC we have developed a procedure for generating and analysing a set of possible long term strategies for Britain's national infrastructure.

Each sector has developed strategies which simulate decisions that can change the infrastructure performance of each sector. These strategies are comprised of sub-strategies which can be more easily assigned as input variables to the models. These sub-strategies represent 1) social and behavioural change (i.e. changes in demand), 2) technological change (i.e. changes to technology efficiency and costs), and 3) systemic change within the physical system of infrastructure assets (i.e. changes to the configuration and capacity of infrastructure networks). Sub-strategies can broadly target 1) demand management and 2) capacity provision summarised as follows:

Demand management sub-strategies:

- *Influencing user behaviour* – User behaviour can be influenced by offering targeted information regarding their use of infrastructure and by other societal pressures. Sector-specific examples include reducing domestic energy use through energy saving schemes, achieving transport modal shift through societal pressure, increasing local levels of grey water recycling by introducing water usage schemes and increased levels of recycling and other resource recovery.
- *Pricing measures* – Taxation and financial incentive policies influence demand for infrastructure services. Examples include road user charging measures, or other regulations or taxes designed to reduce fossil fuel use and promote electric vehicles; tax incentives to encourage investment in new technologies; and per volume tariffs for water consumption or waste generation.
- *Consumer technology* – Demand can also be influenced by technological changes to the way a system is used. For example, increased energy efficiency in domestic appliances, alongside the national roll-out of smart meters is likely to influence energy demand, and increased use of ICT could result in variations in travel habits.

Capacity provision sub-strategies:

- *System efficiency* – Technological advances and different approaches to capacity utilisation can affect the overall efficiency of an infrastructure system. For example, efficiencies in road transport can be achieved through increased fuel economy, optimised route planning or vehicle-to-vehicle interactions.

- *Infrastructure composition* – Changes to the infrastructure system itself will be achieved through new-build i.e. new rail links, motorways, power stations or reservoirs, and adaptation of existing infrastructure, replacing out-dated infrastructure with modern materials, or incorporating new technologies. The transition to renewable energy generation is one example of how the physical infrastructure required for distribution of energy may remain relatively unchanged, but the landscape of options for energy generation might change significantly.

Each sector currently has between 4–8 strategies which have emerged from specific combinations of these sub-strategies for influencing demand and capacity; narratives for these main strategies are listed in Appendix 1. The current report provides interim results for a limited number of strategies for each sector. Our next steps will focus on model implementation for all remaining strategies. However, for the first time, strategies are being combined and harmonised across sectors to develop policy portfolios to assess cross-sector performance.

2.2.3 POLICY PORTFOLIOS

Policy Portfolios are approaches to infrastructure provision that cut across specific infrastructure sectors. This allows assessment of sectoral interdependencies and is used to contrast and compare the cross-sector performance of national infrastructure. Important spatial and temporal trade-offs and synergies are identified in terms of return on investment, environmental performance, capacity expansion and demand reduction. The analysed Portfolios are as follows:

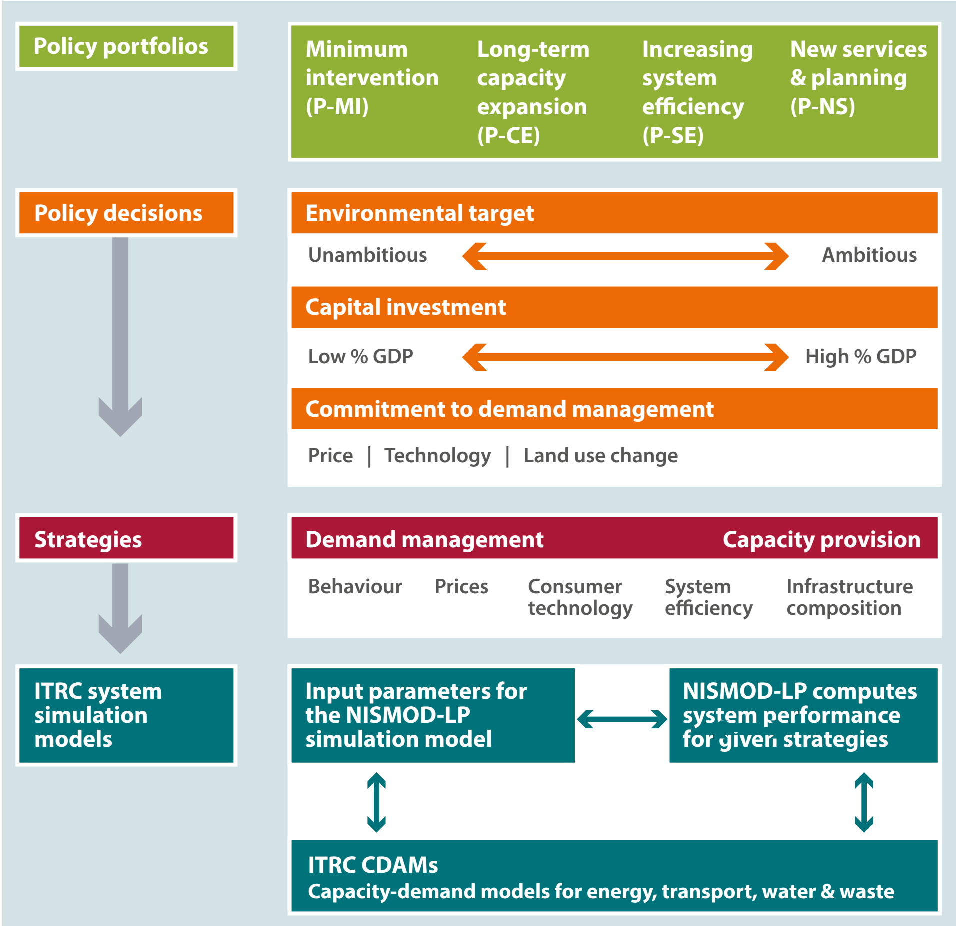
- *Minimum Intervention (P-MI)*: reflects historical levels of investment, continued maintenance and incremental change in the performance of the current system.
- *Long-term Capacity Expansion (P-CE)*: focuses on large scale, long-term investment into physical capacity expansion to meet increasing demand.
- *Increasing System Efficiency (P-SE)*: focuses on deploying the full range of technological and policy interventions to increase efficiency of the current system targeting both supply and demand.
- *New Services and Planning (P-NS)*: focuses on restructuring the current mode of infrastructure service provision through long-term investment in innovation and design of new service delivery models. A combination of targeted centralisation and decentralisation approaches are deployed.

Table 1 categorises the sector level strategies (described in Appendix 1) contained within each Policy Portfolio. This assessment has sampled a subset of strategies contained within each Portfolio to demonstrate the ITRC's approach to assess cross sector performance (Section 5). Although the current results are not yet complete, important differences in terms of investment and carbon emissions between each Portfolio are shown. The Cycle 2 assessment will provide complete results based on full model runs.

Table 1: Headline strategies contained within each policy portfolio				
Minimum Intervention Portfolio (P-MI)				
Energy	**Transport**	**Water Supply**	**Wastewater**	**Solid Waste**
EN0 Minimal policy intervention	TRO Decline and decay	WRO Current trends	WWO Current trends	WEO Current trends
Long-term Capacity Expansion Portfolio (P-CE)				
EN3 Gas world	TR1 Predict and provide	WR5 Local integration WR4 National integration WR7 Local crisis WR8 Uncontrolled demand	WW1 Low environmental aspirations	WE4 Maximum energy WE5 National plan
Increasing System Efficiency Portfolio (P-SE)				
EN1 Local energy and biomass EN2 Electrification of heat and transport	TR2 Cost and constrain TR3 Adapting the fleet TR4 Promo-pricing	WR1 Local resilience WR2 Closed loops WR3 Regional conservation	WW2 Retrofit technologies	WE1 High tech WE3 Deep green
New Services and Planning (P-NS)				
EN4 Balanced transition	TR5 Connected grid TR6 Smarter choices	WR6 National conservation	WW3 New technology	WE2 Closed loop zero waste

Figure 1 illustrates the ITRC guiding hierarchy for developing cross sector Policy Portfolios based on 1) high-level policy decisions, 2) strategic investments to change the system, and 3) model implementation of those options. Specifically, a particular scenario/strategy combination will comprise the exogenous assumptions about the socio-economic and environmental context in which national infrastructure is operated, together with high-level assumptions which determine the willingness to invest in new infrastructure assets, the ambition to decarbonise and mitigate other environmental impacts resulting from infrastructure operation, and the level of commitment to demand management through strong price signals, consumer technology, and level of centralisation and/or decentralisation through planning and design.

Figure 1: ITRC decision and planning hierarchy showing how sector level strategies are compiled into 4 Policy portfolios for the assessment of total system and cross sector performance.



2.2.4 CAPACITY-DEMAND MODULES

Figure 2 shows the overall data flow structure where economics and demographics lie upstream with their inputs as one-way information flows into NISMOD's Capacity-Demand Assessment Modules (CDAMs) for five different infrastructure sectors (Energy, Transport, Water, Waste Water, and Solid Waste). These NI sector models derive demand for infrastructure services and infrastructure capacity. The network representations of the systems of physical infrastructure assets used to derive capacities are common to all the sector models, while the method used to derive demand for NI services is dependent on the model structure. For instance in the energy sector, the capacity model represents the GB electricity and gas generation and supply networks (an expansion of the CGEN modelling and optimization tool (Chaudry *et al*. 2014)), while demand is estimated using a separate disaggregated demand module (Baruah and Eyre 2014); for transport, a national strategic model of trunk road, rail, port and airport infrastructure gives the capacity at regional resolution, while demand is derived using elasticity-based relationships with a set of explanatory variables (Blainey *et al*, 2012); a water resources system model is used, coupled with a model of wastewater treatment facilities; and a national solid waste assessment model gives the outputs for the waste sector (Hall *et al*. 2012).

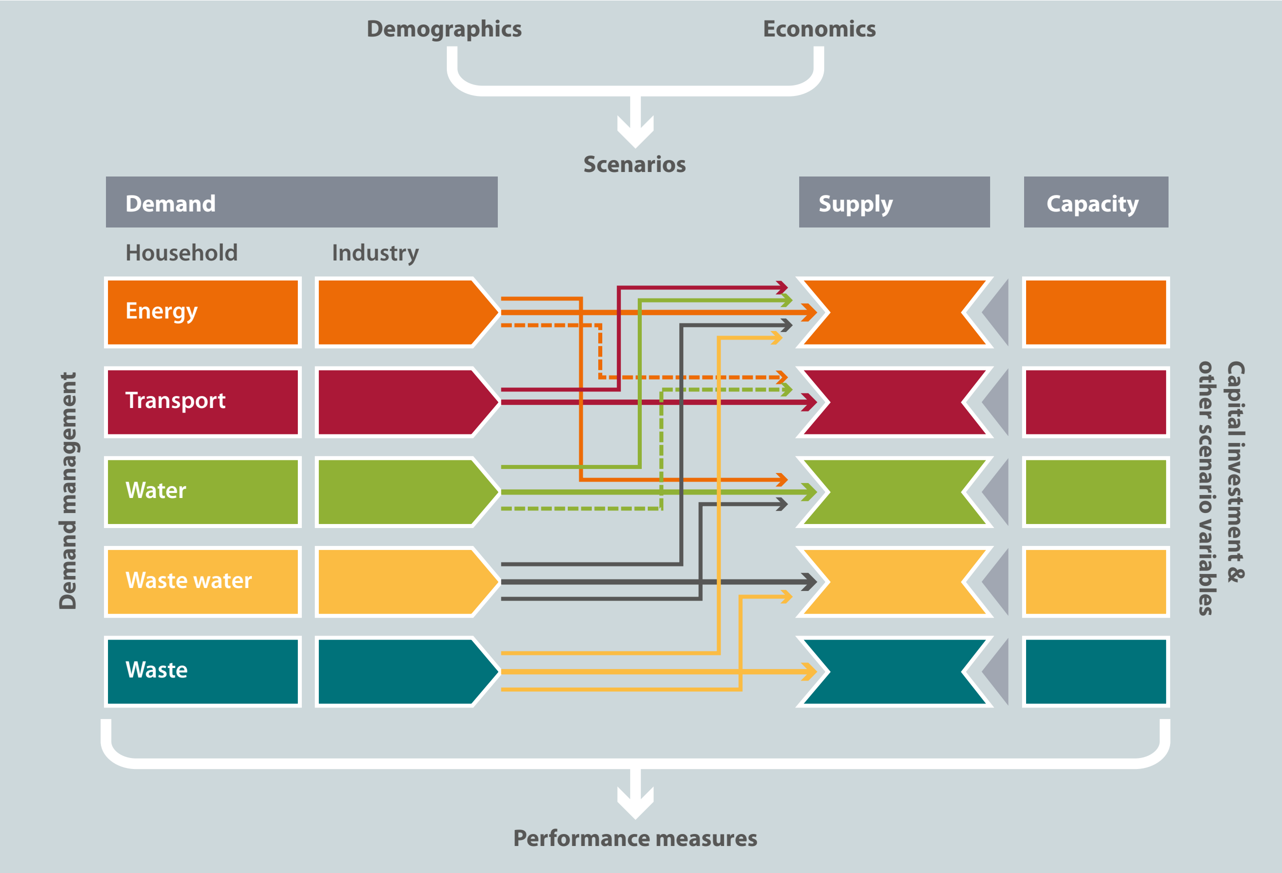
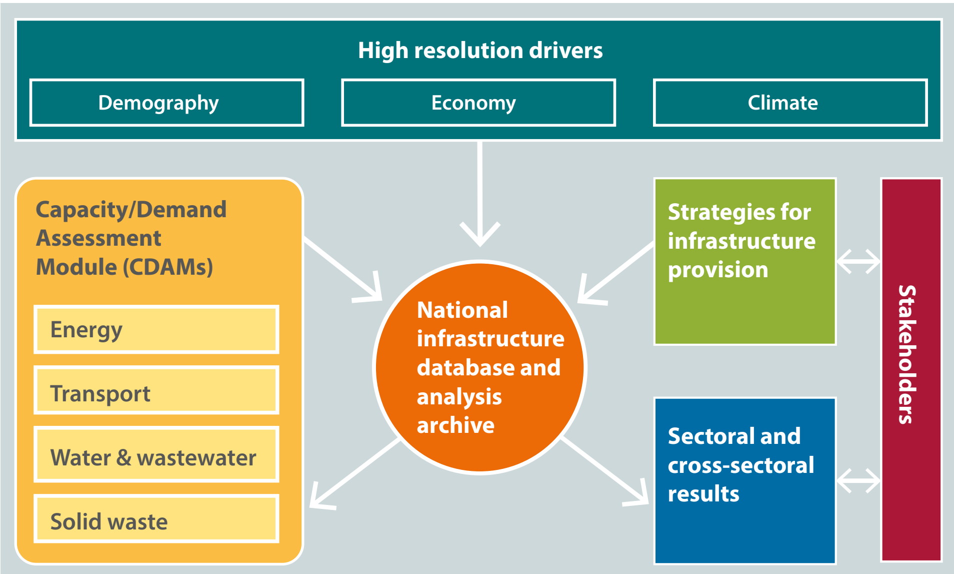


Figure 2: Framework for Capacity – demand modules depicting flow of information and data.

2.2.5 INTEGRATED DATABASE, VISUALISATION AND ANALYSIS

The scenario and strategy modelling outputs are then entered into a common database, which is used for post-processing and visualisation of data outputs. This also allows centralised sampling of model runs and collection of model results. Importantly, this integrated framework allows us to identify and compile Policy Portfolios to assess total system performance and sectoral interdependencies. Figure 3 illustrates how the various modelling components are linked together.

Figure 3: Implementation structure of the general model framework; consisting of Capacity and Demand modules (CDAMs) for each NI sector, socio-economic models to define possible future demographic and economic conditions, the central database, and the routines for sampling, post-processing, and visualisation across the different infrastructure strategies.



An important innovation of the integrated database is to develop advanced visualisations of model outputs to facilitate cross-sector analysis. This is being developed into an interactive infrastructure visualisation dashboard which can be used for research, decision-making, and broader engagement with stakeholders. Figure 4 is an example of a dashboard comprised of a web-based interface showing a central stylised map of GB, which allows clicking on single regions/locations/infrastructure items to choose sector and location for producing reports about infrastructure performance. Additional drop-down menus allow choosing the time, scenario, and strategy dimension as well. The interface can host multiple reports at the same time, which allows comparative analyses across multiple dimensions (scenarios, strategies, spatial, temporal). Next steps will focus on full database integration and visualisation capacity for each sector, where data outputs (demographics, economics, energy, transport, water, waste) can be selected, combined and visually overlaid allowing for cross-sectoral analysis.

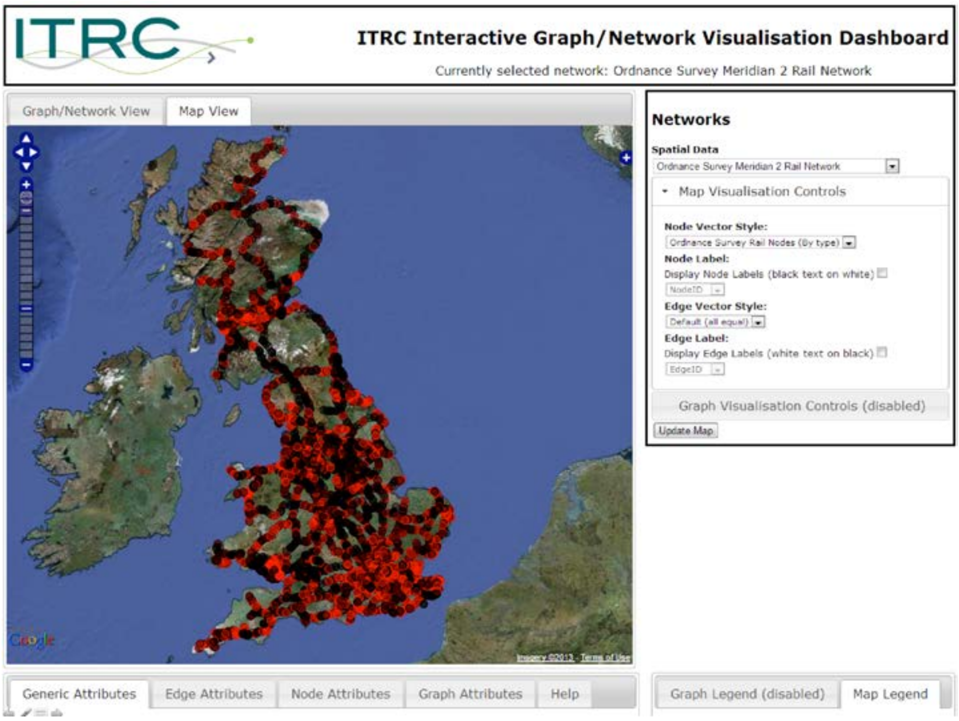


Figure 4: Example of infrastructure visualisation dashboard – National scale UK rail network. Each data point can be selected for site specific resolution and additional data.

3 Drivers and trends in infrastructure demand

Infrastructure assets are long-lived, so decisions today must take account of expected future trends, and the nature of these long-term trends is uncertain and hard to predict. Future demand and stresses for infrastructure provision will depend on a range of factors such as future population, national wealth and climate change. The following analysis presents the range of long-term projections of economic and demographic change in the UK. These scenarios represent a set of alternative plausible future conditions for infrastructure planning, which provide a consistent and cross-cutting framework for the analyses of demand and supply of the different infrastructure sectors.

3.1 POPULATION AND DEMOGRAPHICS

The population projection model is driven by three components: fertility (birth rate), mortality (death rate) and migration. These three drivers of population change are interdependent. To explore the range of potential demographic futures a consistent framework is required to determine how each component should be varied relative to the others. Scenarios have been specified by combining parameter settings ('high' or 'low') of these three model drivers (fertility, mortality and migration), taking account of co-dependency between them. Cutting across these drivers is a 'prosperity' dimension which has a positive influence in population. For example, low mortality would be expected under a high prosperity scenario, with the opposite occurring with low prosperity.

Migration is estimated by calculating the difference in the size of the projected population (by age group) for a given region compared to the expected ONS regional projection. This residual can be assumed to be the result of migration. Due to unavailable data, calculating migration is not possible at this stage. However, having constrained the number of births and deaths for each region the residual difference between the projection here and the ONS sub-national projection is a result of net migration. Therefore this residual is assumed to represent migration and is added to the sub-national population for the year being projected. As with the fertility and mortality scaling factors, net migration totals are stored for each age group in each projected year. After 2033 (when there are no sub-national projection data) linear regression is used to find a trend in male and female migration totals, and these trends are used to estimate migration post 2033.

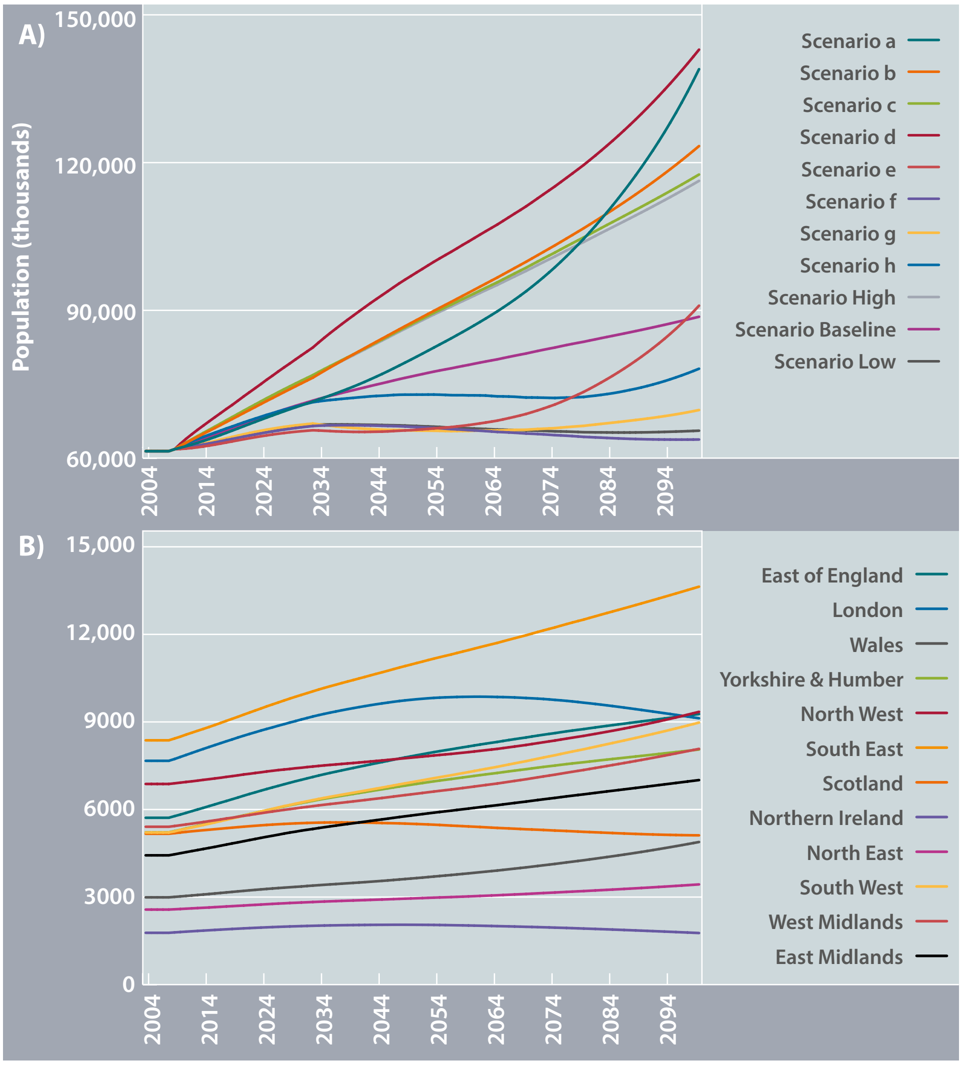
We have developed three scenarios, each with a high and a low dimension resulting in a total of 8 different scenario combinations. By summing the specified values for each scenario it is possible to identify the behaviour of each model component under the 8 scenario combinations. The following provides key results for 1) population growth, 2) ageing, and 3) urbanisation and the implications for future infrastructure demand in GB.

3.1.1 POPULATION GROWTH

Scenario results indicate that an important overall trend in the population projections is simply 'growth'. For example, in the baseline all regions will experience growth in the range of 20–35% before 2100 (Figure 5A). This has direct and significant implications in terms of demand for infrastructure services, across all sectors. The following summarises the key results for population shown in Figure 5A and B:

- At the national level, higher prosperity scenarios (Scenarios a, b, c, d) lead to higher population growth due to the lower mortality rates. It is important to note that the higher range population projections are only meant to demonstrate the upper range in sensitivity of the modelling capability. We recognise that the upper level population projections, while consistent with our modelling assumptions are highly unlikely. We therefore use the baseline population projection for the sector level models to assess the performance of different strategies.
- At the regional level, the population of the south-east of Great Britain is growing faster than the north-west in all of the 8 scenarios.
- Migration policy has a considerable impact on the regional population trend especially for London. The more conservative policies (Scenarios a, c, e, g) will lead to a relative higher population growth in London than the surrounding government office regions GORs, while for more liberal policies (Scenarios b, d, f, h), population growth in London is lower than in the surrounding areas (i.e. South East, East of England etc.).
- Higher population growth can be found in the North West than in the surrounding areas (i.e. Yorkshire and the Humber and North East) under Scenarios g and h.
- There is a mismatch between population growth and infrastructure availability. Pressure on existing facilities, for example, growth in the south-east where transport congestion is highest; modest growth in Scotland where resources such as water are most abundant.

Figure 5: A) Total population change for 8 scenarios (d – highest; f – lowest) compared against ONS high, low and baseline projections to 2100; B) Baseline population projection disaggregated by UK Government Offices Region (GOR).



3.1.2 AGEING

The population structure is expected to age markedly in every region under all future scenarios (Figure 6). A more elderly population has important policy impacts in terms of the kinds of transport services that need to be provided (e.g. investment in appropriate public transport) but also in relation to varying patterns of consumption for energy, water and waste.

The relatively slow uptake of information technology amongst more elderly consumers is also important for example, by not leveraging the full potential of efficiency improvements such as accessing integrated transport services or energy demand management in households. However, the age profile varies significantly both geographically and between scenarios. Naturally, scenarios involving high migration and relatively slow growth in life expectancy (for example, Scenario h) will give rise to younger age pyramids, which may trigger increased demand for NI services, which may negatively impact the service network where it is already constrained for example in the Southeast region.

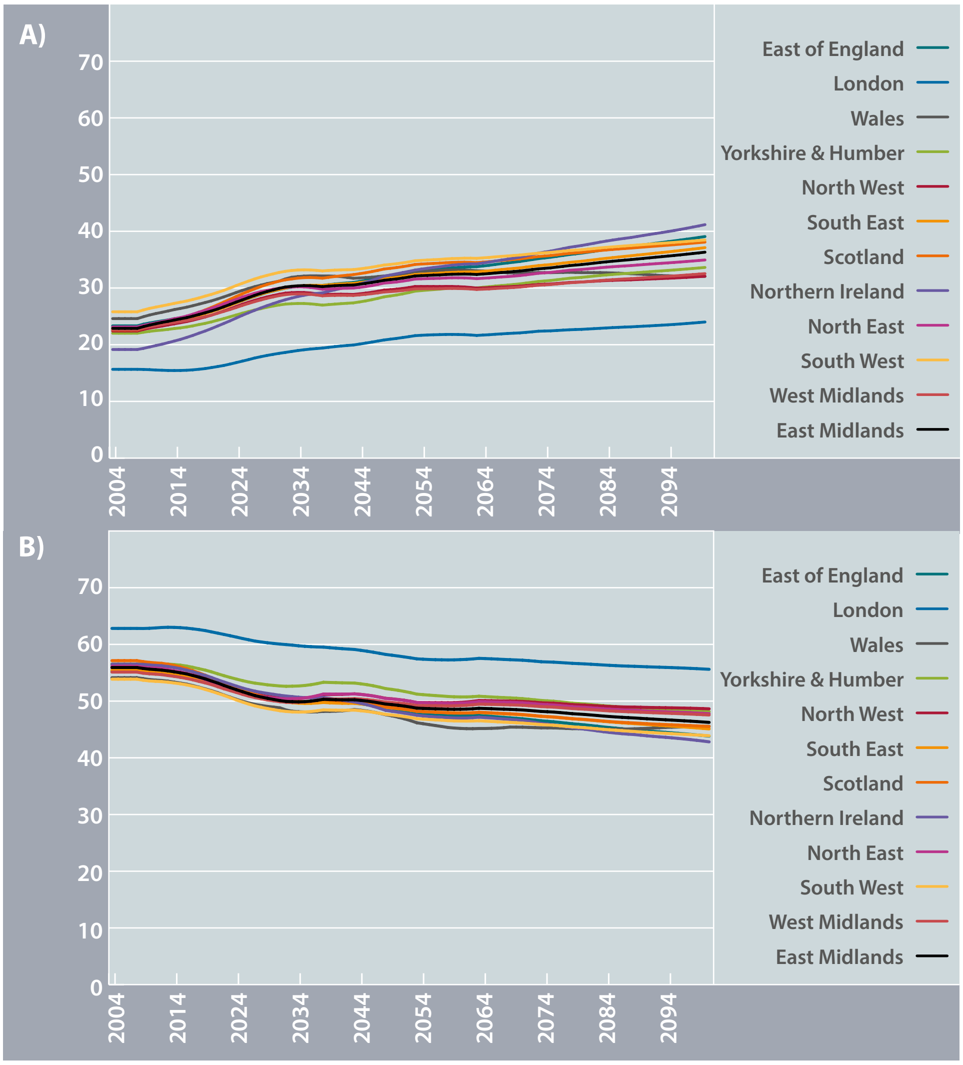


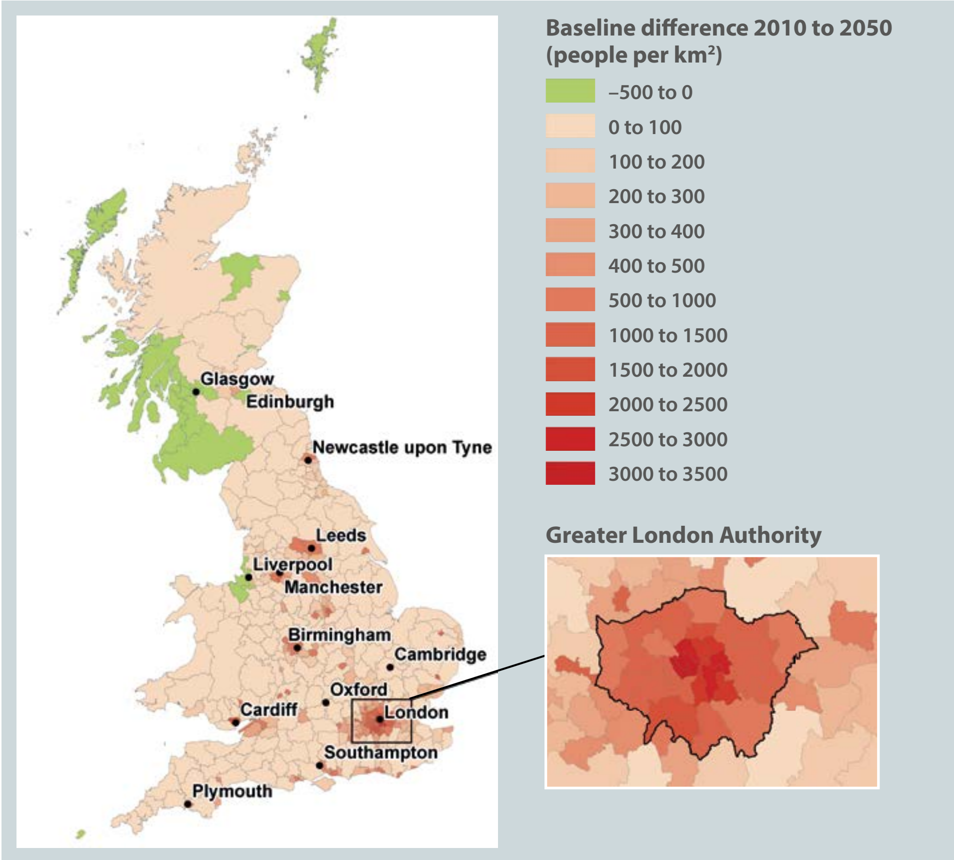
Figure 6: A) Proportion of retiree by region; B) Proportion of working age population by region (baseline model).

3.1.3 URBANISATION

Figure 7 shows that the prospects for urbanisation vary markedly across regions and between scenarios. The balance of demographic growth between rural and urban areas is an important question with potentially profound implications for infrastructure policy. For example, counter-urbanisation might be relatively favourable for the future provision of waste sites and would take the pressure off congested urban road networks; conversely, it might encourage use of space for the construction of larger properties with greater household energy and water requirements, and increase the demand for transport between rural and urban areas.

Urbanisation also has governance implications (Section 6). In the UK, local authorities have become increasingly active in some infrastructure sectors (e.g. energy), whilst in others they have traditionally played a central role (e.g. waste and transport). This has opened up opportunities for more co-ordination of infrastructure development at a local level, albeit in the context of severe limitations on local government finances.

Figure 7: Population density change by Local Authority District (LAD) using Baseline Scenario (2010–2050).



3.2 MACROECONOMIC DRIVERS OF DEMAND FOR INFRASTRUCTURE SERVICES

World economic growth (i.e. outside of the UK) affects UK economic performance through changes in prices and patterns of trade. Meanwhile, the direct effect of an increase in population is an increase in the level of UK household expenditure and different regional demands for NI services. If the national infrastructure stock is to meet the needs of a growing economy it is essential to forecast how the demand for each of the key sectors of infrastructure may change. Economic scenarios have been generated from Cambridge Econometrics' (CE's) MDM-E3 model of the UK economy. These scenarios are based on the following key sets of assumptions:

- UK population by region – these used the 8 demographic scenarios discussed above (Section 3.1) as direct inputs for generating economic scenarios;
- World economic growth – these were developed by CE to represent a range of world economic conditions that affect UK international trade with the rest of the world. Three variants are used:
    - Central: a baseline view with non-UK economic growth averaging 3.5% p.a. over 2010–2020, and 4–5% p.a. over 2020–2050;
    - High: average non-UK economic growth of 4% p.a. over 2010–2020, rising to 5–6% over 2020–2050; 3)
    - Low: non-UK economic growth of 2% p.a. over 2010–2020 and growth of 3–3.5% p.a. from 2020–2050.

- Fossil fuel prices – these are based on the UK Department for Energy and Climate Change (DECC) fossil fuel-price assumptions from the most recent Updated Energy and Emissions Projections publication extended to 2050 (DECC, 2012). Three nominal price variants are used shown in Table 2.

Table 2: Fossil Fuel Price Assumptions in 2050 (Nominal)

	Central	High	Low
Oil ($/bbl)	245	496	204
Gas (p/therm)	183	263	105
Coal (£/tonne)	199	313	126

Source: DECC Updated Energy and Emissions Projections, CE calculations.

The three assumption sets outlined above represent the complete scenario space of economic projections. Combining all variations results in a possible 72 scenario projections.

3.2.1 NATIONAL ECONOMIC SCENARIOS

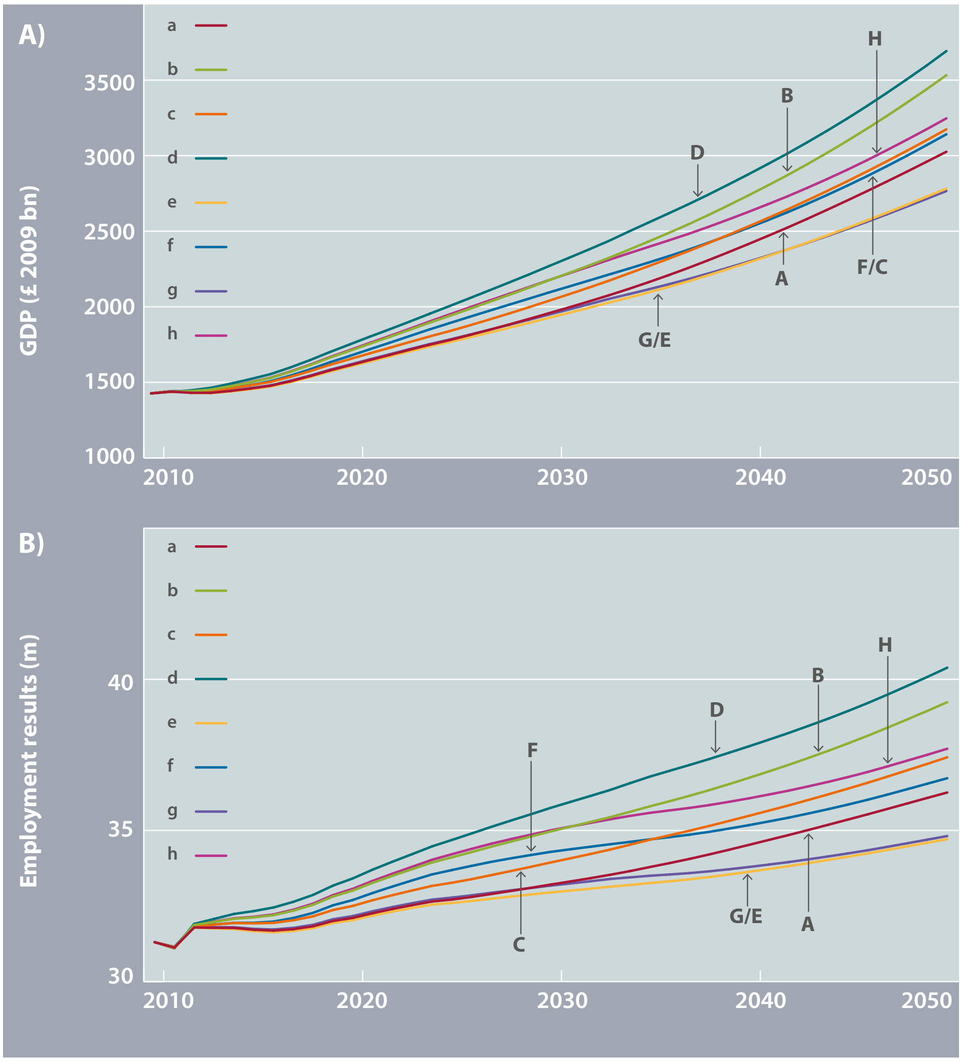
Figure 8A shows the range of Gross Domestic Product (GDP) outcomes from 8 population scenarios. The Central assumptions on world economic growth and fossil fuel prices have been used in all cases to isolate the effects of differences in population only. The total range of GDP across scenarios is ~£2.7–3.7 trillion by 2050. Scenarios E and G have a GDP outcome which is 8% less than the central case A. The highest scenario D generates a GDP outcome 22% higher than A.

Figure 8B shows the range of employment outcomes from the population scenarios, which mirrors the GDP results. Compared to Scenario A, employment in Scenarios E and G is 4% lower in 2050 whereas in Scenario D employment is 11% higher.

The direct effect of an increase in population is an increase in the level of UK household expenditure, principally on services rather than manufacturing. While some population scenarios are similar in their projections of total population, their corresponding demographic structures are not. These structural differences (i.e. proportion of working age) introduce supply-side differences in the availability of labour, altering wages and household incomes. The scenarios indicate that services will continue to dominate GVA by 2050, with most activity in London and the surrounding regions, a reflection of the continued dominance of these regions in the underlying population projections.

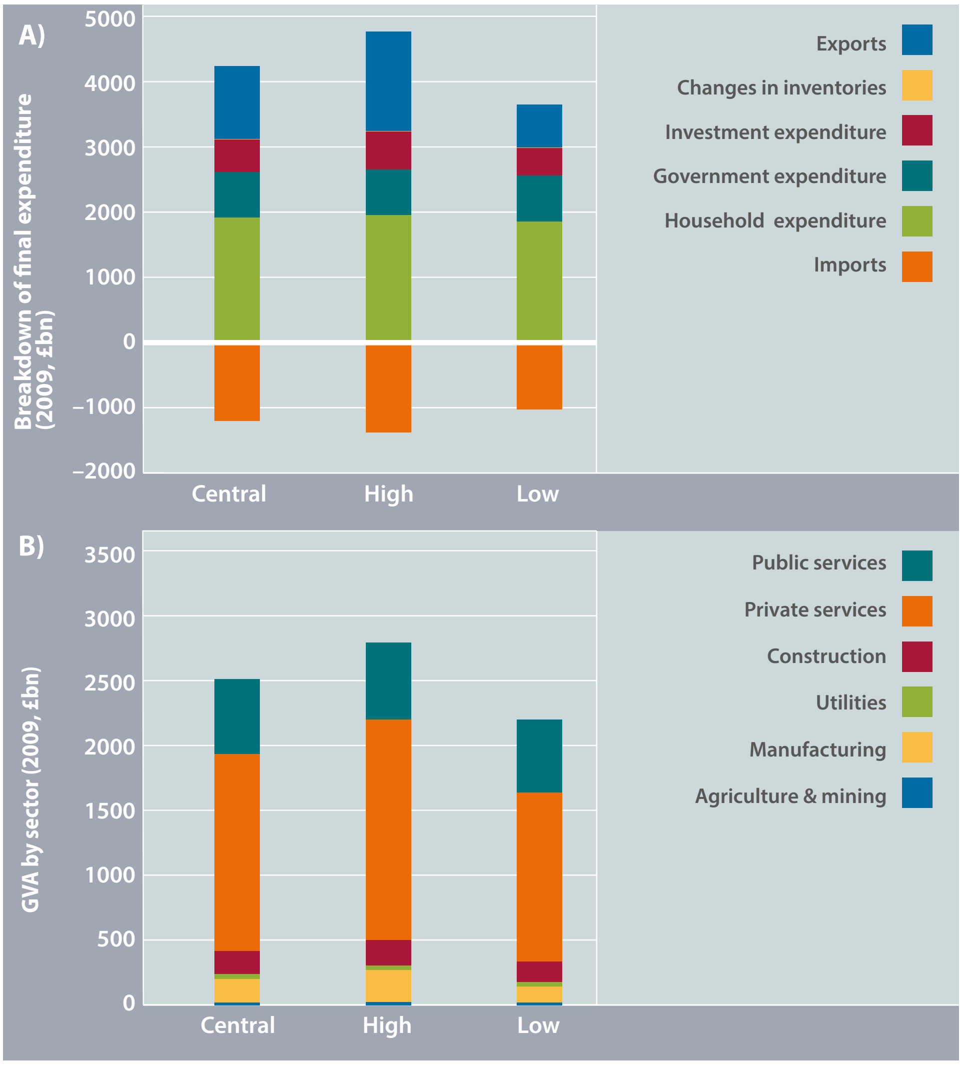
Figure 9A shows the breakdown of GDP by final expenditure indicating that the changes in world economic growth drive the differences in GDP through export demand. However, household expenditure and imports from changes in national income, and investment to support higher/lower levels of UK output also have an indirect impact on the differences between scenarios. Figure 9B breaks down UK Gross Value Added (GVA) by sector. In 2050, services continue to dominate in all scenarios in 2050, but changes in export demand are also reflected in larger differences in manufacturing GVA compared to that seen in the population-only scenarios.

Figure 8: A) Gross Domestic Product (GDP) and B) employment results for each population scenario (2010–2050).



The differences in fossil-fuel prices, in macroeconomic terms, are relatively small in this analysis. While the differences in nominal wholesale prices are large (40% either side of the baseline), after factoring in other components of the price, the difference in the final retail prices is smaller. This leads to relatively minor changes in energy demand in the scenarios, which feed through into relatively small changes in industrial cost structures. With utilities accounting for a small share of UK GVA, the overall macroeconomic impacts are fairly minor both in terms of their ability to drive a different GDP trajectory and to effect changes in economic structure. As such, the economic impacts of the fossil–fuel price variants are much smaller compared to the other input assumptions such as population growth.

Figure 9: A) Breakdown of final expenditure and B) Gross Value Added (GVA) by sector for each world economic growth scenario in 2050.

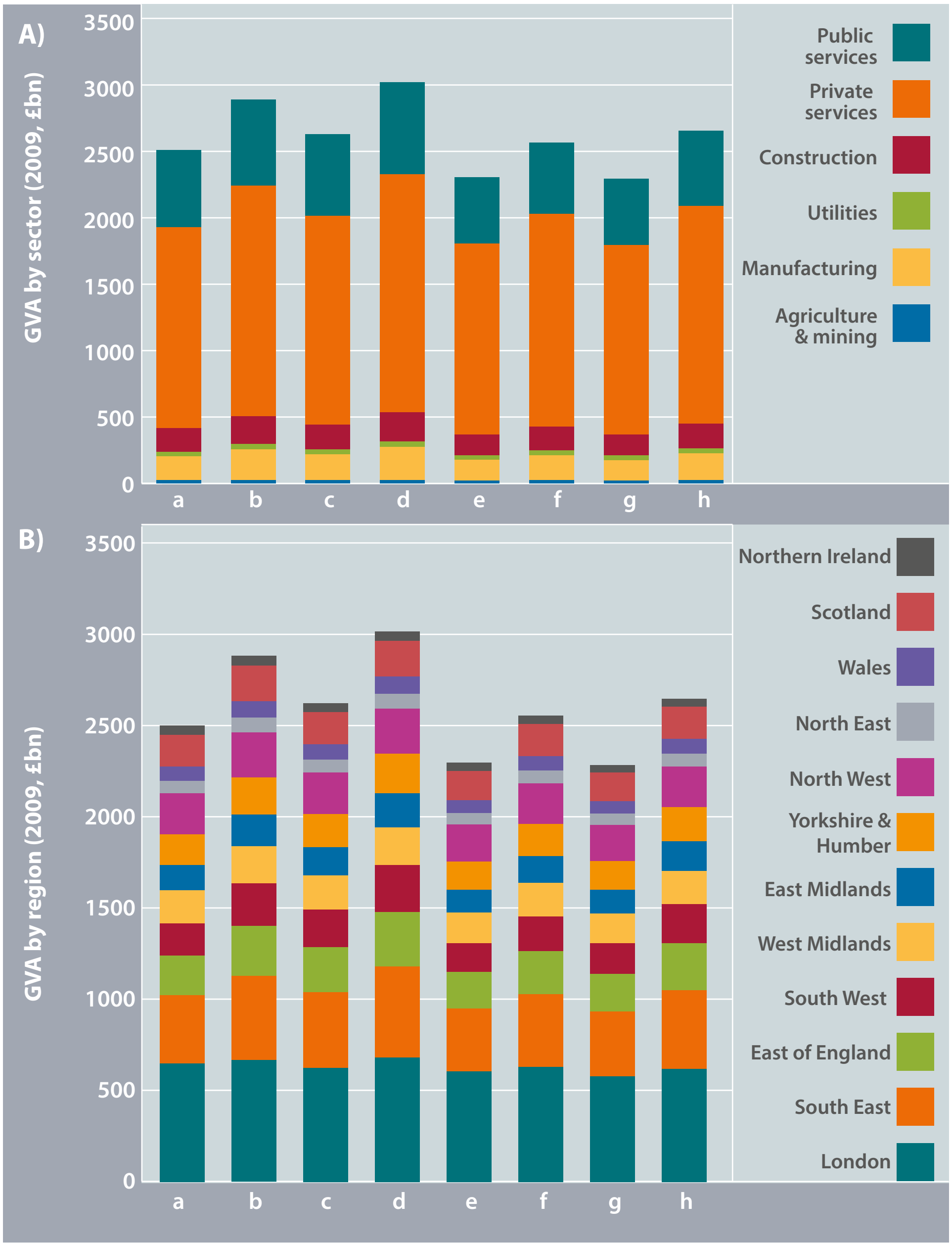


3.2.2 REGIONAL ECONOMIC TRENDS

In terms of spatial distribution of the population (Figure 10B), London and the surrounding regions continue to dominate in all 8 population scenarios. This means that the regional distribution of economic activity (with large amounts of this related to services) does not differ substantially across our scenarios.

The results show that as might be expected structural change usually occurs slowly, especially at the regional level within the UK. Even when significant shifts in industrial structure occur, which has certainly been the case in the UK over the last forty years, the impact on the distribution of activity spatially tends to be smaller because of the existing balance of economic activity in the UK. London and the South East already account for one third of UK output; in order to 'catch up', the other regions would need to achieve considerably faster than average growth sustained over a number of decades. This has not happened over the last fifty years.

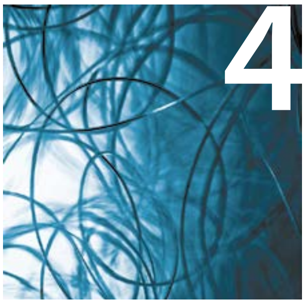
Figure 10: A) (top) Breakdown of Gross Value Added (GVA) by sector and B) (bottom) region for each population scenario in 2050.



3.3 KEY MESSAGES

- Differences in growth trajectories can be achieved through a wide range of alternative economic structures (e.g. internal/population/services vs. external/world/manufacturing) albeit to a lesser degree. The model scenarios have very different implications for infrastructure service provision and future network configuration. The composition of the growth trajectory is clearly of significant importance in determining the parts of the infrastructure system that will be challenged the most for example, how changes in economic structure under different scenarios affect the ability of the economy to provide sufficient energy and water, or dispose of waste. Demand for energy will be shaped to some extent by these structural changes, along with measures in place to target the UK's greenhouse gas emissions reduction commitments. Increased demand for water is expected to grow most rapidly where economic activity and population is concentrated – regions of the UK where collection will be most limited, so for the water supply sector redistribution will continue to present a key challenge, along with the ageing and deteriorating distribution network. Illustrating the interdependencies between the infrastructure sectors, there is potential for further expansion of facilities and networks located to serve densely populated areas where the management of solid waste recovers resources that can be used for energy generation.

- There are also a number of impacts that result from changes in demographic structure, particularly as they affect the supply of the working population that could merit further investigation and trends in the way we work will shape demand for infrastructure services. A larger proportion of the workforce will have jobs in services, in professional and managerial occupations, in which there is greater potential to telework and for flexible working. This may ease transport congestion at peak commute times, but change the pattern of energy demand away from shared offices to (potentially less efficient) individual homes. However, some work may become more transport intensive, requiring more journeys: a larger proportion of the workforce will have more than one job; and the number of some peripatetic jobs, such as social care, is projected to increase as the population ages.
- The transition strategies pursued and investments made by infrastructure sectors will shape future infrastructure networks and their potential to facilitate, or hinder, economic growth.



4 Sector analyses

Options for infrastructure provision in the energy, transport, water and waste sectors have been analysed with national infrastructure models in the NISMOD system. Here we report on this analysis focussing upon the following key issues and related questions:

Capacity provision:

- What are the trade-offs in provision of new capacity versus cost?
- When will capacity constraints be critical in each sector?
- Where should additional capacity be provided? What are the regional variants/ options in provision of new capacity?

Demand management:

- What level of demand restraint could be achieved compared to unrestricted demand and how can this be achieved?
- What are the trade-offs associated with vigorous demand management?
- Are synergies achievable in demand management by taking a cross-sectoral approach?

Carbon reduction:

- What is the cost of meeting carbon targets?
- How do different socio-economic scenarios and infrastructure strategies affect these costs?

Alternative infrastructure pathways:

- What is the potential of ICT to transform infrastructure provision in the future? How should we plan for or enable this now?
- Is a highly decentralised future of infrastructure provision a viable strategy, given current network configuration and available technology? How might we achieve such provision and what would be the costs and benefits?

4.1 ENERGY

Major investments are anticipated in electricity generation and distribution in order to maintain and increase capacity, meet the UK's greenhouse gas emissions reduction commitments and address EU directives. The UK energy infrastructure system may be divided into three broad sub-systems: electricity, gas, and liquid and solid fuels.

Electricity infrastructure is the most capital intensive in terms of both generation capacity and networks (high voltage (HV) transmission and low voltage (LV) distribution). Electricity generation is dominated by fossil fuels (gas (24%) and coal (44%)) with a declining but substantial share of nuclear (20%) and a small but rising share of renewables (10%) (DECC, 2013). Electricity supply is split roughly equally three ways between homes, non-domestic buildings and industry. Use in transport is currently small.

The gas infrastructure consists of the high pressure (HP) transmission and Liquid Petroleum (LP) distribution networks, and the interconnectors and liquid natural gas (LNG) terminals for gas imports. The latter are increasingly important as North Sea gas supply declines. Gas is a major source of energy to power stations (24%), industry (38%) and buildings (68%) (DECC, 2013), although there has been a slow decline in the latter categories in recent years due to improved energy efficiency.

Liquid fuels, predominantly petroleum, are used mainly in transport, where they are the dominant energy source. Uses in industry and power generation have declined substantially since the 1970s, although there is some residual use in homes that are not connected to the gas network. They are moved to some extent by pipelines, but mostly by road and rail.

Solid fuels (coal and some biomass) are used very largely for power generation. They are also transported via road and rail. Transport infrastructure is therefore critical to liquid and solid fuel supply, and is not further addressed in this section.

4.1.1 APPROACH

The NISMOD analysis of **Energy Demand** is comprised of 3 explicit demand models for residential, services and industrial sectors. Estimation of transport energy demand involves conversion of transport services demand from the NISMOD transport model. A separate peak demand model estimates yearly electricity and gas peak load evolution based on total yearly and sectoral energy demands. Residential, services and industrial demand models use an accounting-simulation modelling approach aimed at estimating spatial-temporal changes in energy demand from a base year, and for a given set of demand scenarios (demography and economic output) and sector strategies. Three strategies are modelled (See Appendix 1 for strategy narratives):

1. Minimum Policy Intervention (MPI) used as the reference case;
2. Electrification of Heat and Transport (EHT); and
3. Local Energy and Biomass (LEB).

All strategies use the central case population and economic scenario as exogenous inputs. The demand outputs are then used as inputs for the energy supply model. Base year 2010 demands for the 3 economic sectors are from DECC (2013). Base year space heating demands are temperature corrected prior to simulation.

Energy Supply is modelled using the combined gas and electricity model (CGEN+) which is an optimisation model for energy infrastructure expansion planning. The model simultaneously minimises energy infrastructure expansion and operational costs. A power generation expansion module determines the type, capacity, location and time that generating plants need to be built in an optimal manner. Network expansion is implemented by adding new assets such as pipes, compressors, and storage facilities in the gas network and increasing transmission line capacity in the electricity network. CGEN+ is also capable of modelling a simplified hydrogen and carbon capture and storage (CCS) infrastructure. Resource limitations (economic and materials), efficiency gains and growing energy demand are the main drivers for the need to build optimal energy networks. The model establishes least cost development paths for gas and electricity for alternative supply and demand scenarios and strategies.

The energy supply model assesses the MPI strategy including a simulated carbon price floor (EMR package) for 2013 (£ 16/tCO_2), 2020 (£ 30/tCO_2) and 2030 (£ 70/tCO_2), and three supply side variants for the EHT strategy assuming high take up of carbon capture and storage (High CCS), offshore (High Offshore), and nuclear (High Nuclear).

4.1.2 KEY RESULTS

Total energy demand: Figure 11 A and B show a wide range of future possible demand for electricity depending on socio-economic scenarios, potential new demands (electric vehicles and heat pumps) and efficiency improvements. In addition, demands on electricity infrastructure can be reduced by 'own generation' in industry and buildings, notably by photovoltaic (PV) and combined heat and power (CHP). Demand on electricity infrastructure increases by 37% and 85% respectively from 2010 to 2050 with the MPI (used as the reference case), and EHT strategies. Despite moderate population and GDP increase and significant demand from transport electrification, the LEB strategy reduces 2050 electricity demand to the 2010 level with implementation of ambitious efficiency measures and use of electricity from PV and CHP. Electricity demand in the LEB strategy is 37% and 55% less than in the MPI and EHT strategies respectively, and 17 TWh of PV generated electricity is exported to the grid.

Residential sector energy demand: Figure 12 shows that the EHT and LEB strategies produce contrasting levels of electricity demand with a comparable level of total gas consumption. With aggressive penetration of heat pumps, the EHT strategy reduces sectoral gas consumption by ~80% below the MPI strategy by 2050. In the residential sector, despite efficiency measures (both in housing fabric and heating efficiency), gas consumption in LEB is somewhat higher than EHT, highlighting the importance of heat pumps in reducing gas demand to very low levels. In industry, the higher application potential of biomass systems than heat pumps for fuel switching is highlighted by a smaller gas demand in LEB than EHT.

Figure 13 shows residential sector demand by end-use indicating that demand reduction measures in LEB are achieved through more efficient appliances. Heating system efficiency improvements have historically been effective in reducing demand. However, switching gas boilers to heat pumps (in LEB this occurs at half the level of EHT) means space and water heating final energy consumption in LEB is still somewhat higher than in EHT. The figure also highlights that there can be multiple different strategies producing similar levels of total energy demands.

Figure 11: A) Electricity demand from all sectors, including potential losses at base year level; B) Sectoral natural gas demand, excluding for electricity generation for MPI, LEB and EHT strategies.

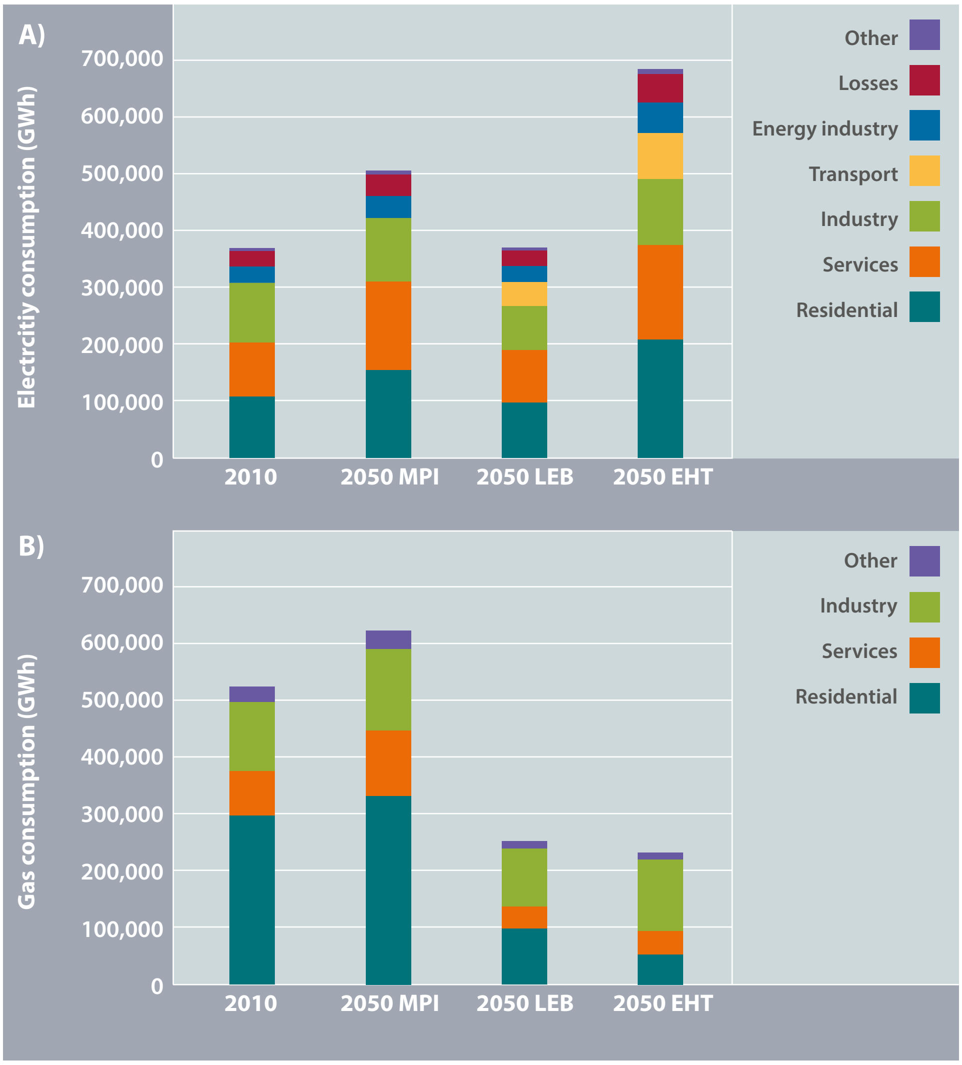


Figure 12: Residential sector energy demand by fuel carriers for MPI, LEB and EHT strategies.

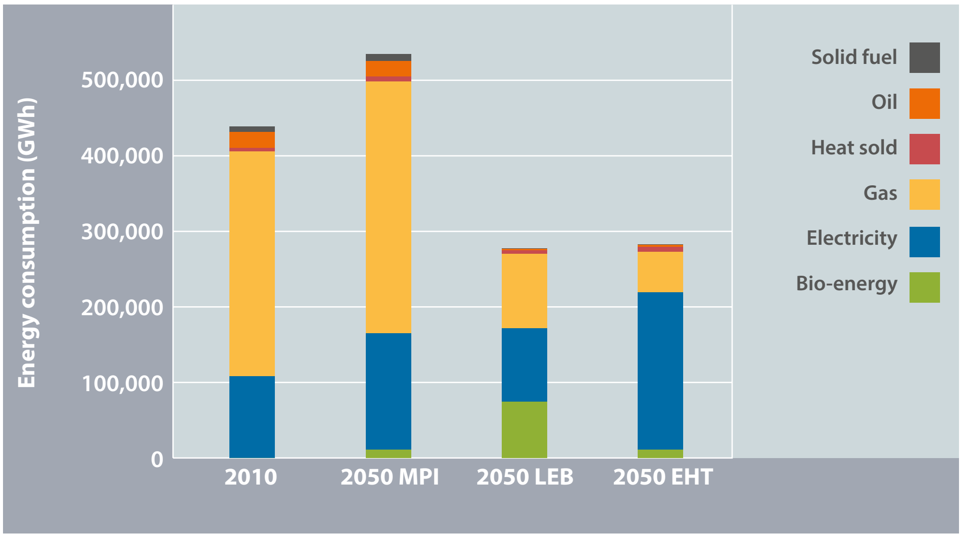
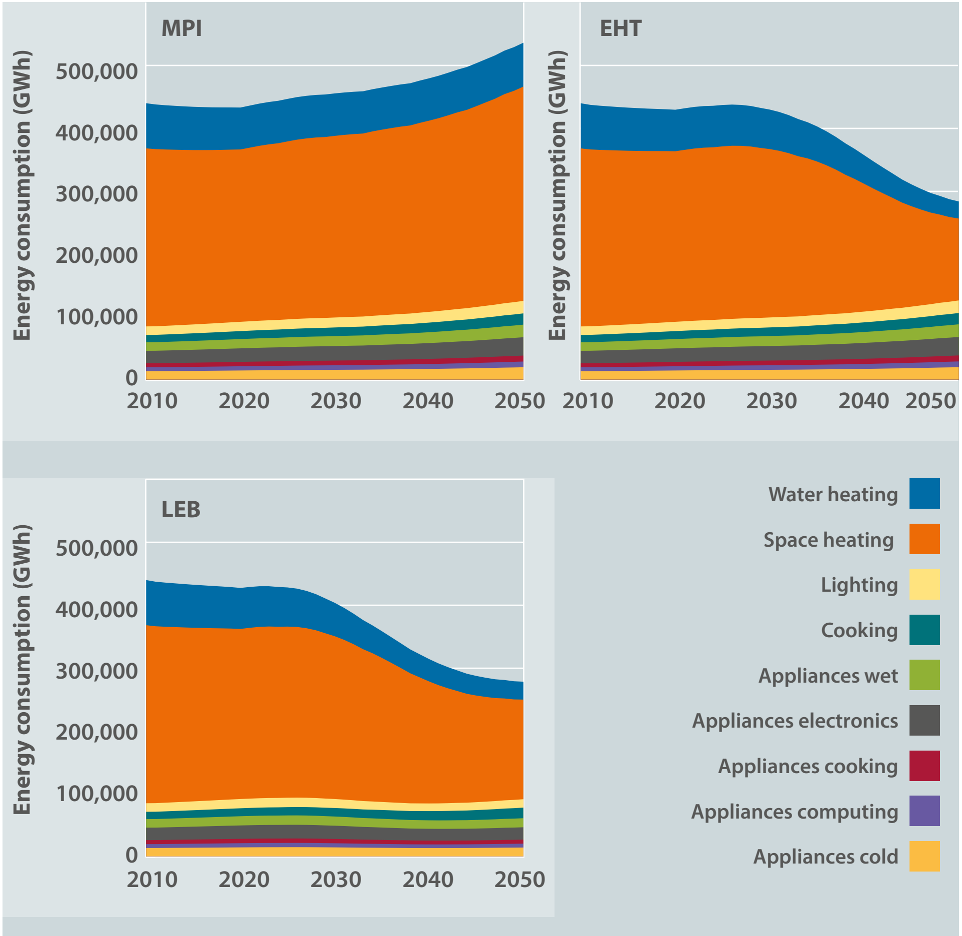


Figure 13: Residential sector energy consumption by end-use for MPI, EHT and LEB strategies.



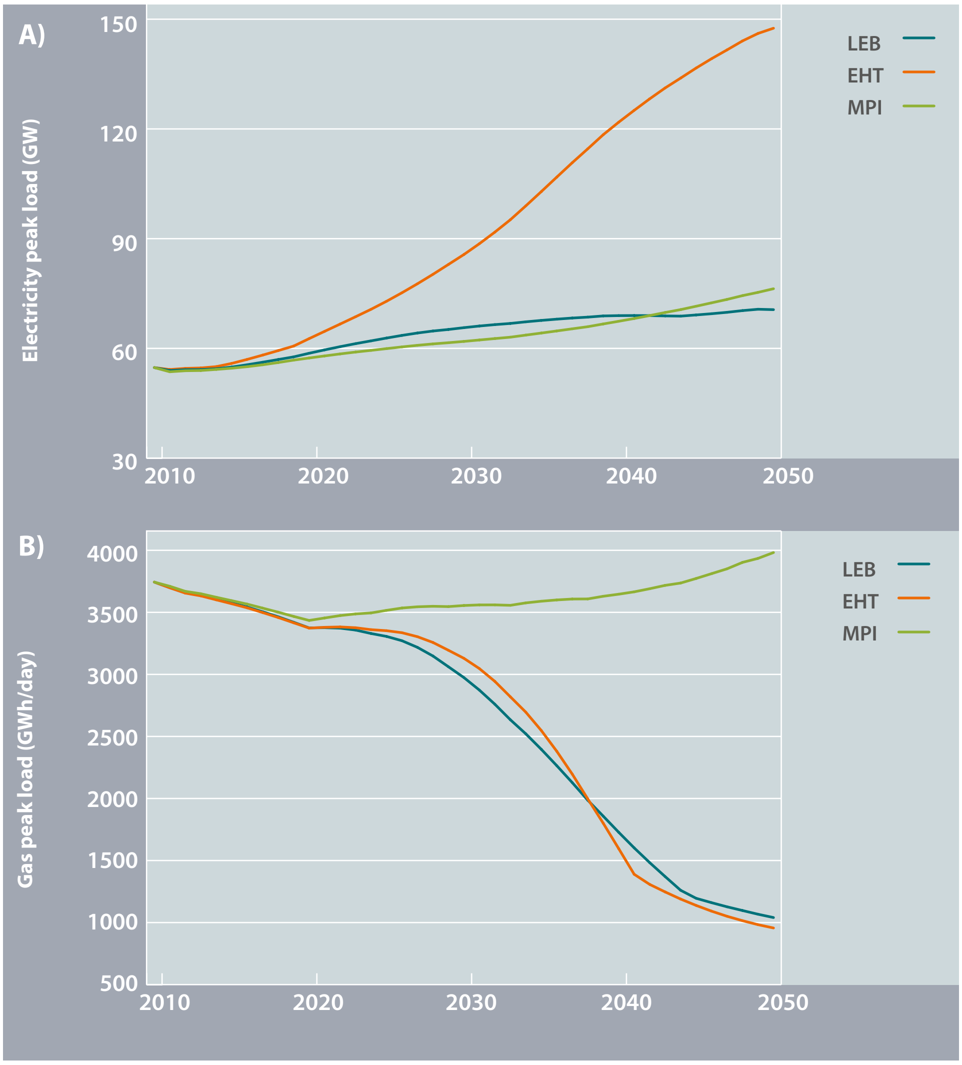
Peak energy demand: Demand implications for infrastructure need assessment of both total and peak energy demand in key fuel carriers. Figure 14A and B show that the LEB strategy uses 27% less electricity demand than MPI strategy by 2050 due to more aggressive efficiency measures and fuel switching, yet its electricity peak is just 7.5% below MPI's by 2030 due to higher electric vehicles and heat pump penetration. With EHT, peak electricity demand increases by 93% over MPI to 147.5 GW (almost three times the current level). In contrast, while total and peak gas demand decrease by 63% and 73% respectively by 2050.

This differing evolution of electricity and gas peak demands highlight contrasting challenges for energy supply infrastructure. In EHT, there are significant implications for both electricity infrastructure (from expansion) and existing gas infrastructure (from disuse and decommissioning). In LEB, electricity infrastructure implications have some similar characteristics but much less pronounced than in EHT, whereas the gas infrastructure implications are similar.

EHT strategy assumes, during peak hours, 20% of EV/PHEVs connected for charging and 10% providing V2G demand response. Increasing V2G connection percentage by 10% (to 20% V2G) is found to decrease system peak load by ~7% to 137.9 GW from 147.5 GW.

Electricity generation capacity: Strategies for provision of new electricity generation capacity are shown in Figure 15. The capacity of CCGTs in 2050 is high in all strategies. CCGT capital costs are lower than coal plants, and therefore always more economic at low load factors. In strategies where there is a carbon price floor (currently £16/tCO_2 rising to £30/tCO_2 by 2020), coal plants are also relatively expensive to operate. CCGT capacity in the high nuclear and offshore strategies is exceptionally high. This is in part to deal with inflexible (nuclear) and variable (wind, wave etc.) generation and to meet peak demand.

Figure 14: Peak A) electricity and B) gas demands for MPI, LEB and EHT strategies.



The large amount of capacity in the EHT strategies (in comparison with MPI) is due to increasing electrification of heat and transport. This results in high annual energy and peak demand requirements almost two times larger than in the MPI strategy. Generation capacity is even higher (>300 GW) in the offshore EHT scenario due to the variable output of wind turbines.

Investment in power transmission infrastructure: Figure 16 shows the amount of transmission capacity added for all strategies disaggregated by region from 2010–2050. There is a direct correlation between the transmission capacities added and the amount of new generation capacity connected to the electricity network, as shown in Figure 15. Results indicate that for MPI, transmission investment takes place in the 2020s (~8 GW additional by 2050). This is mostly due to the connection of offshore wind in Scotland, with similar results for MPI with carbon cost. There is no significant difference between MPI with or without a carbon cost on transmission expansion. With EHT-Nuclear, transmission investment takes place from 2020-2050 (~18 GW additional by 2050), whereas with EHT-CCS transmission investment takes place in the 2020s (~7 GW additional by 2050). The costs of CCS infrastructure have not been calculated in this figure, with the assumption made that the infrastructure cost is embedded in the cost for CCS technologies (the capital costs of CCS generation capacity include the cost of the infrastructure needed). For EHT-Offshore, transmission investment takes place from 2020-2050 (~65 GW additional by 2050) to accommodate large amount of renewable/offshore technologies in the system.

Figure 15: Power generation capacity for different strategies.

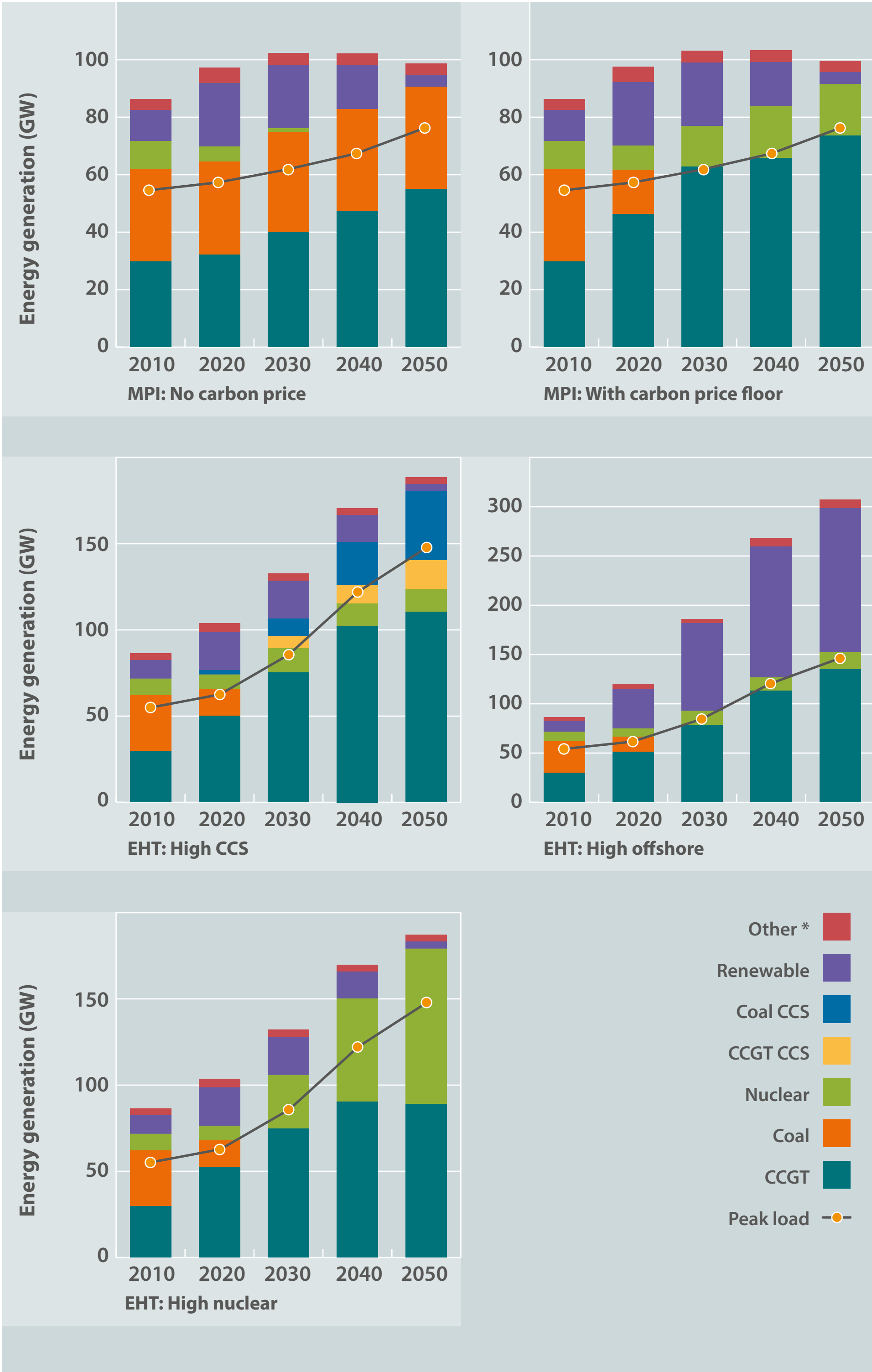
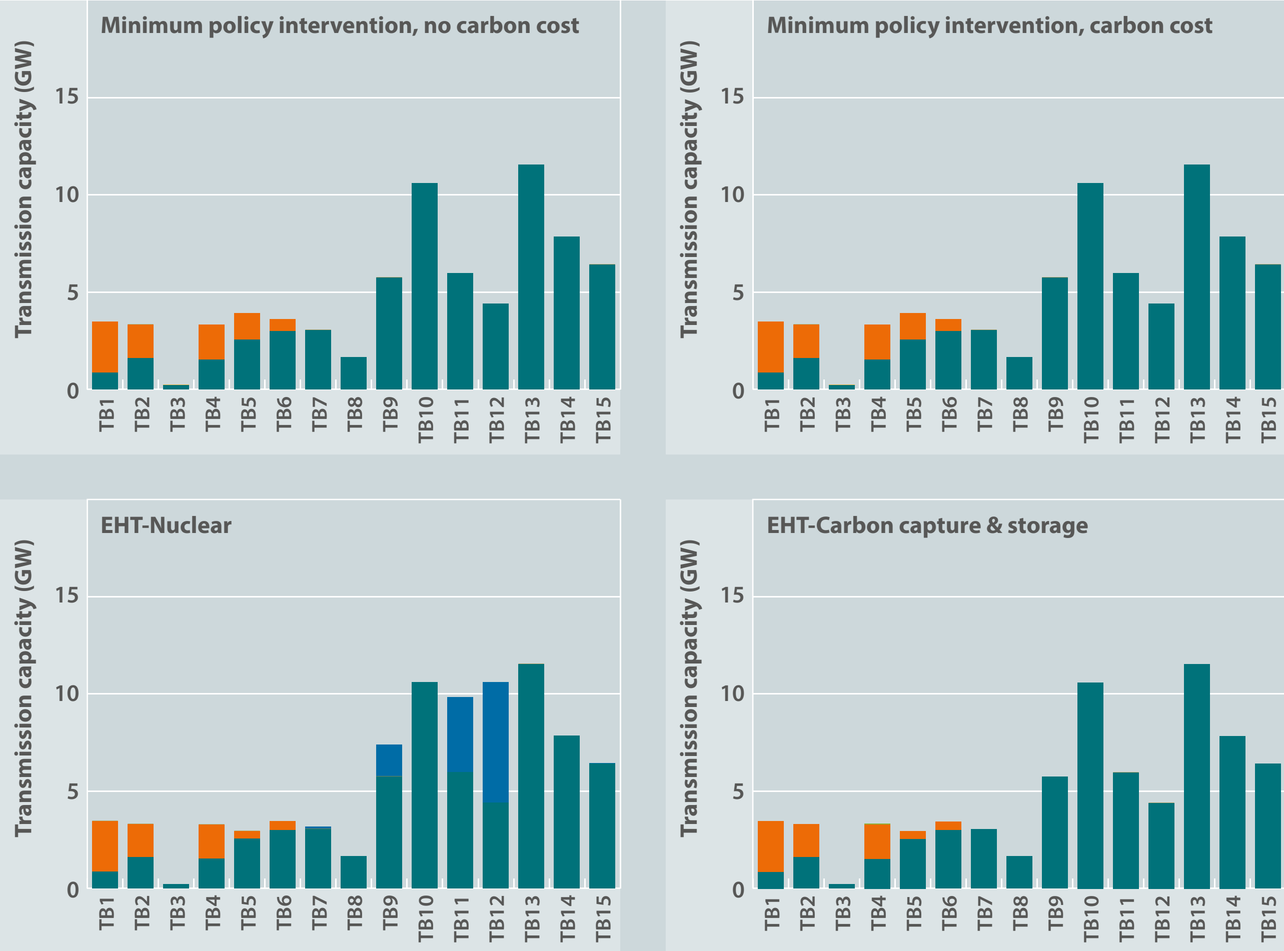
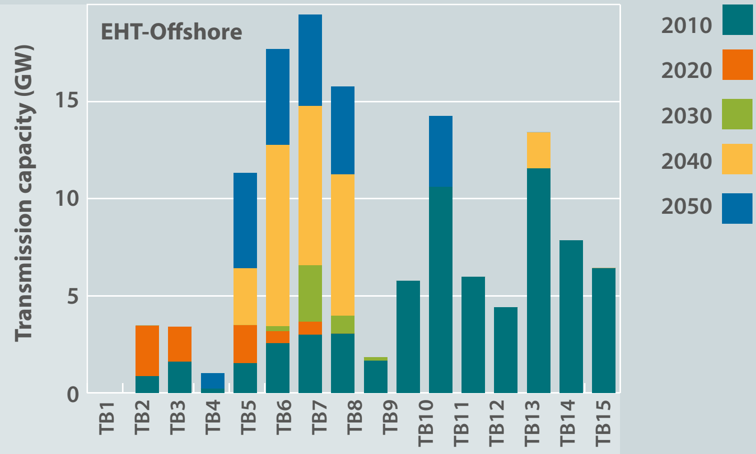
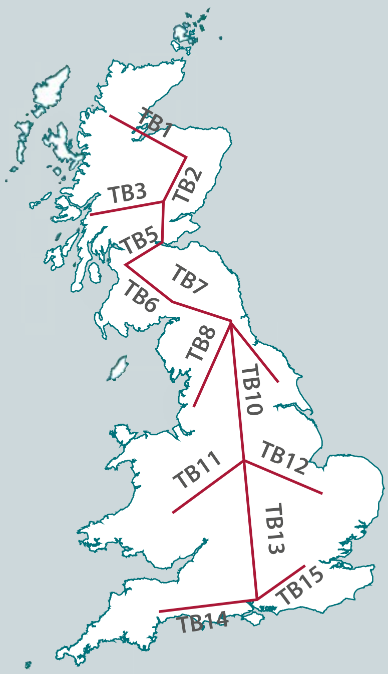


Figure 16 (overleaf): Power transmission network investment for MPI and EHT-Nuclear, EHT-CCS, EHT-Offshore strategies (2010–2050).



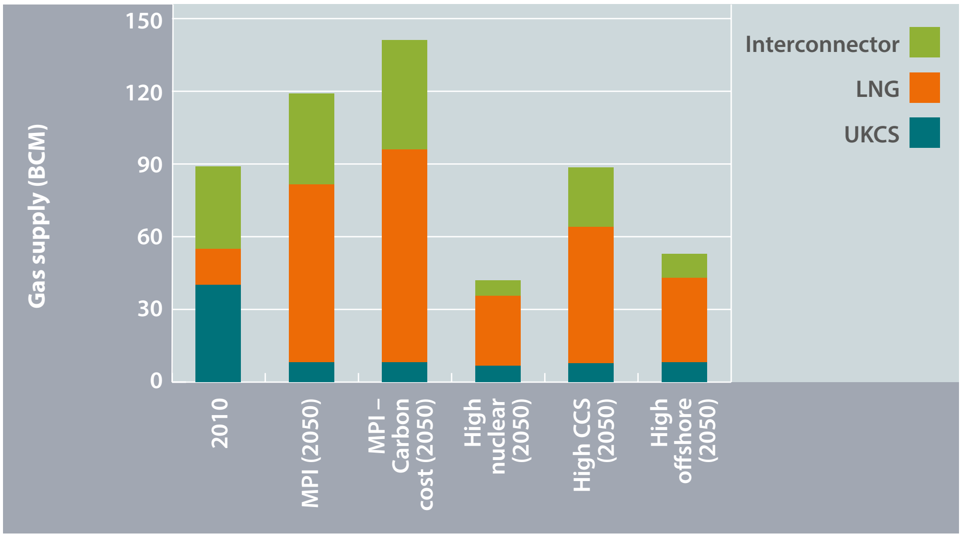




Strategy (cumulative GW)	2010	2020	2030	2040	2050
MPI – No carbon cost	67.05	75.17	75.17	75.18	75.18
MPI – Carbon cost	67.05	74.22	74.26	74.27	74.27
EHT-Nuclear	67.05	73.98	73.98	73.98	85.81
EHT-CCS	67.05	73.98	74.03	74.03	74.04
EHT-Offshore	67.05	74.71	78.97	108.56	132.07

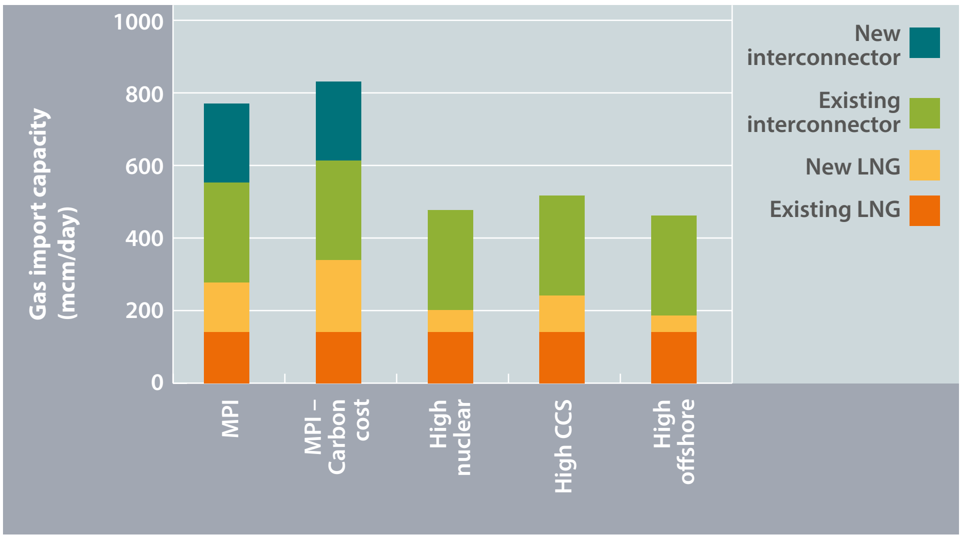
Gas supply: Gas supplies follow very different trends, but in all strategies (Figure 17) show some common features. As current sources of gas decline (first UKCS and then Norwegian imports) the slack is taken up by imports from Eurasia across the continent interconnectors and increasingly by LNG, which makes up the bulk of gas supplies from 2030 onwards. The development of a significant UK shale gas industry is possible, but very uncertain, and would principally substitute for LNG imports. The scale of gas supply is very different with significant rises in the MPI strategies (especially where coal has a fiscal disincentive), but reductions in all EHT strategies, especially where there is limited reliance on CCS.

Figure 17: Gas supplies for different strategies.



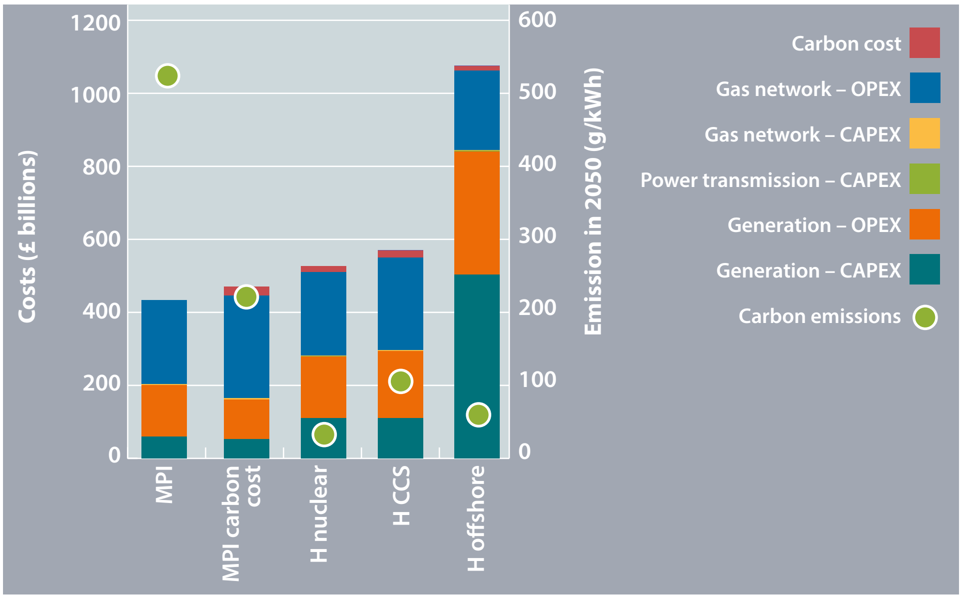
Gas Import Capacity Expansion: The cumulative gas import capacity expansion is shown in Figure 18. In all strategies LNG terminal expansion is prevalent. Lower levels of gas system expansion take place in the EHT strategies due to considerably lower gas demand for the heating sector which has been electrified. In all cases, development of a UK shale gas sector would be likely to substitute for LNG capacity.

Figure 18: Gas import capacity for different strategies.



Total Investment and Carbon Emissions: The total discounted cumulative costs (2010-2050) and carbon emissions (2050) from electricity generation for all strategies are shown in Figure 19. In the EHT strategies it can be seen that electricity system capacity and operation accounts for the bulk of costs out to 2050 as the overall energy system is electrified. The emissions from the electricity system range from business as usual in the MPI strategy to low and very low in the CCS and nuclear/offshore strategies.

Figure 19: Total discounted costs (2010) and emissions from the electricity sector.



4.1.3 KEY MESSAGES

- Fuel switching is key to achieve major reduction in carbon emissions and can assist in reducing total energy consumption, particularly in the residential and services sectors. Heat pumps are key to deliver significant fuel switching from gas to electricity. Bio-energy could also be significant.
- Large-scale electrification of heat and transport has major infrastructure implications. The transport sector would require new electric fuelling infrastructures. The electricity grid has to be upgraded (smarter grid, new transmission lines and distribution reinforcements) and additional generation capacity will be needed. With decreasing gas use, alternative usage or decommissioning of existing gas infrastructure has to be addressed. Even aggressive demand reduction, if coupled with moderate electrification of heat and transport, mean that requirement for electricity infrastructure will be at least as high as at present.
- The three strategies (MPI, EHT and LEB) that have been adopted in this assessment are contrasting, posting a stark choice about the direction in which the energy infrastructure system should be taken. An EHT strategy provides large energy and carbon reduction opportunities, both by increasing efficiency by fuel switching and greater potential for supply decarbonisation. However, EHT requires new infrastructure on a very large-scale and the security of supply from generation diversity reduces, with very high dependence on the electricity system.
- Energy efficiency (and microgeneration as an 'on-site' provider) can reduce both total and peak energy demands. This will reduce both the costs and environmental impacts of new infrastructure.

4.2 TRANSPORT

Demand for transport infrastructure has grown steadily over the years for a variety of reasons, including economic growth combined with relatively low costs making travel affordable for most, population growth and societal changes such as increasing numbers of female drivers. Growth seems likely to continue, although demand for passenger car transport may reach a saturation point (Millard-Ball & Schipper, 2010). Continued growth in demand will result in increased congestion and delays, particularly on roads and rail, which will in turn tend to inhibit further growth. Building new transport infrastructure will alleviate congestion and delays in the short term but will also induce further demand. If transport costs continue to increase this will inhibit demand, and so adversely affect the economy, unless transport growth can be decoupled from economic development.

Carbon reduction targets will drive development in vehicle and fuel technologies and result in increased use of electric vehicles on roads, increased rail electrification and lower use of oil-based fuels. This will require substantial investment in energy infrastructure, particularly for electricity. For example, port infrastructure requirements would be affected by changes to shipping if fuel import patterns were to change in the future.

The transport infrastructure system comprises the trunk road network, the rail network, major airports and major seaports. Although vehicles are not normally considered to form a part of 'infrastructure' they are an important in terms of vehicle technology and alternative fuels. Measuring the performance of transport systems is complex because (i) performance is highly variable both geographically and temporally, and (ii) unlike other sectors there is no assumption that 'security of supply' should be preserved – whilst undesirable, congestion is commonplace on the network. Thus a range of metrics are employed to track the performance of the transport network, including: vehicle kilometres, passenger kilometres, tonne kilometres (freight), delays on the trunk road network, CO_2 emissions, investment, and fuel and energy use.

4.2.1 APPROACH

NISMOD simulates transport capacity and demand across Great Britain for road and rail transport within and between 144 zones, and for air and sea transport at 28 airport nodes and 30 seaport nodes. The model uses a set of elasticities to adjust demand and capacity utilisation levels at yearly intervals from 2011 to 2100, based on changes in both exogenous (population, GVA and energy costs) and endogenous (fuel mix, fuel efficiency, speed/ delays, pricing, and actual and effective infrastructure capacity) variables. The model incorporates feedbacks between capacity utilisation and speed/delays as well as absolute capacity constraints, and includes functionality to model a range of policy options such as congestion and carbon-based tolls, workplace parking levies, rail electrification, 'smarter choice' measures, and specific infrastructure enhancements.

There are currently 7 strategies that can be modelled targeting a range of demand and supply side measures shown in Table 3. The model was run for each of the seven strategies under three combinations of the external scenarios, which were: (i) high population growth, high economic growth and low energy costs; (ii) medium population growth, central economic growth and central energy costs; (iii) low population growth, low economic growth and high energy costs.

Table 3. Transport strategies

	Strategy name	Demand change	Structural change	Capacity (utilisation)/ Supply change
TR0	Decline and decay	TD1 – Uncontrolled decline	TS0 – No change	TC1 – Reduced
TR1	Predict and provide	TD2 – Unconstrained growth	TS1 – Widespread expansion	TC0 – No change
TR2	Cost and constrain	TD3 – Managed decline	TS2 – Minor retrenchment	TC1 – Reduced
TR3	Adapting the fleet	TD0 – No change	TS0 – No change TS4 – Network electrification	TC0 – No change TC3 – Sophisticated vehicles
TR4	Promo-pricing	TD4 – Spatial redistribution	TS0 – No change	TC0 – No change
TR5	Connected grid	TD5 – ICT replacement	TS0 – No change TS4 – Network electrification	TC2 – Increased
TR6	Smarter choices	TD6 – Smarter choices TD5 – ICT replacement	TS3 – Local enhancements	TC0 – No change TC4 – Sophisticated behaviour management

See Appendix 1 for strategy narratives.

4.2.2 KEY RESULTS

Road: Figure 20A shows the total interzonal road traffic across Great Britain with the baseline (TR0) strategy for the three external scenarios. This shows that there is considerable variation in the patterns of traffic growth between the scenarios. Under all three scenarios traffic growth eventually levels out as the road network becomes full to capacity, with this point being reached approximately 50 years later under the low growth scenario than under the high growth scenario.

Figure 20B combines the NISMOD forecasts with observations of traffic volumes for the period 1949–2010, and shows that, when considered as a whole, the high growth forecast is most consistent with observed behaviour over this period. However, the observed growth trend has flattened out in recent years, and if this trend continues then it is possible that even the low ITRC forecasts may be too high.

Figure 21 shows growth in intrazonal road traffic under six of the seven transport strategies using the central external scenario. Strategy TR1 is not shown as this assumes that new infrastructure would be built as soon as capacity utilisation reached 90% of the maximum possible level. In the majority of cases it is clear that road traffic growth plateaus in the second half of the 21st century as infrastructure becomes full up. Transport demand growth is likely under all strategies, but growth is constrained by the supply of infrastructure. There are two exceptions to this general pattern.

The first exception is strategy TR5, which simulates a future where improvements in ICT lead to the substitution of ICT use for travel in relation to certain trip purposes, such as commuting to work, personal business and shopping. While other trip purposes such as home delivery, commuting to education, business travel and leisure would not be affected, the strategy assumes that trip rates per person reduce by 1% per year throughout the modelling period. This reduction in trip rates means that traffic growth initially occurs at a lower rate than under

Figure 20: A) Aggregated GB Road Traffic and Average Speeds Under Strategy TR0 B) Observed and Forecast Aggregate GB Road Traffic 1949–2050.

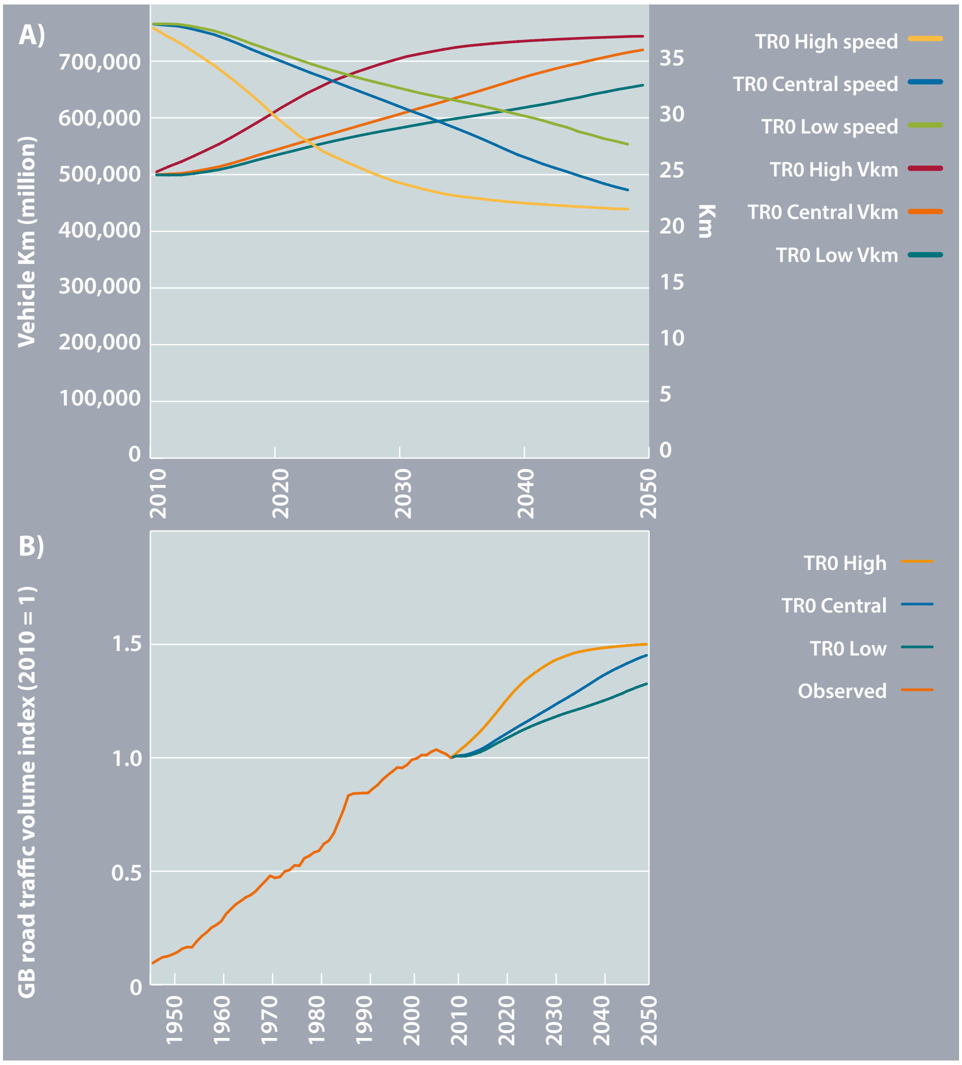
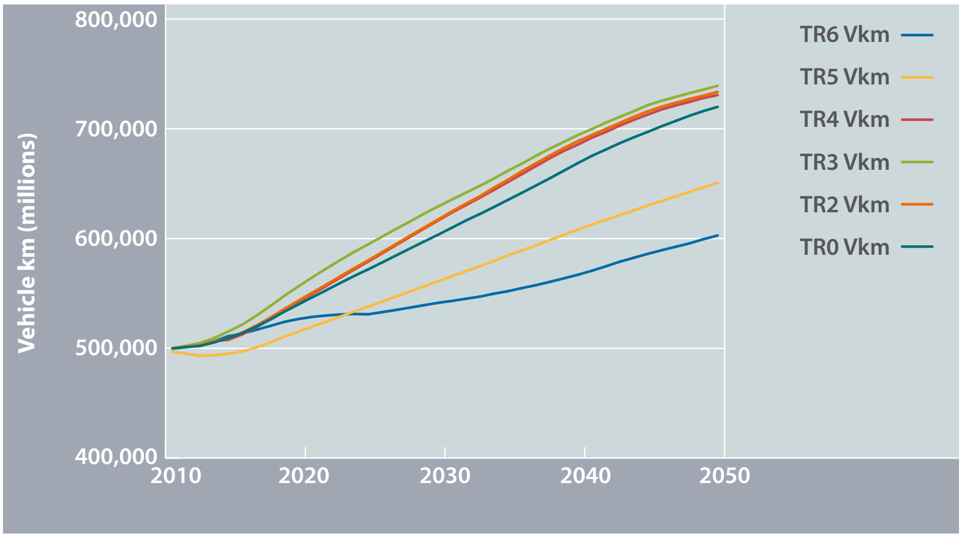


Figure 21: Aggregated GB road traffic under central scenario with strategies TR0 and TR2-6.

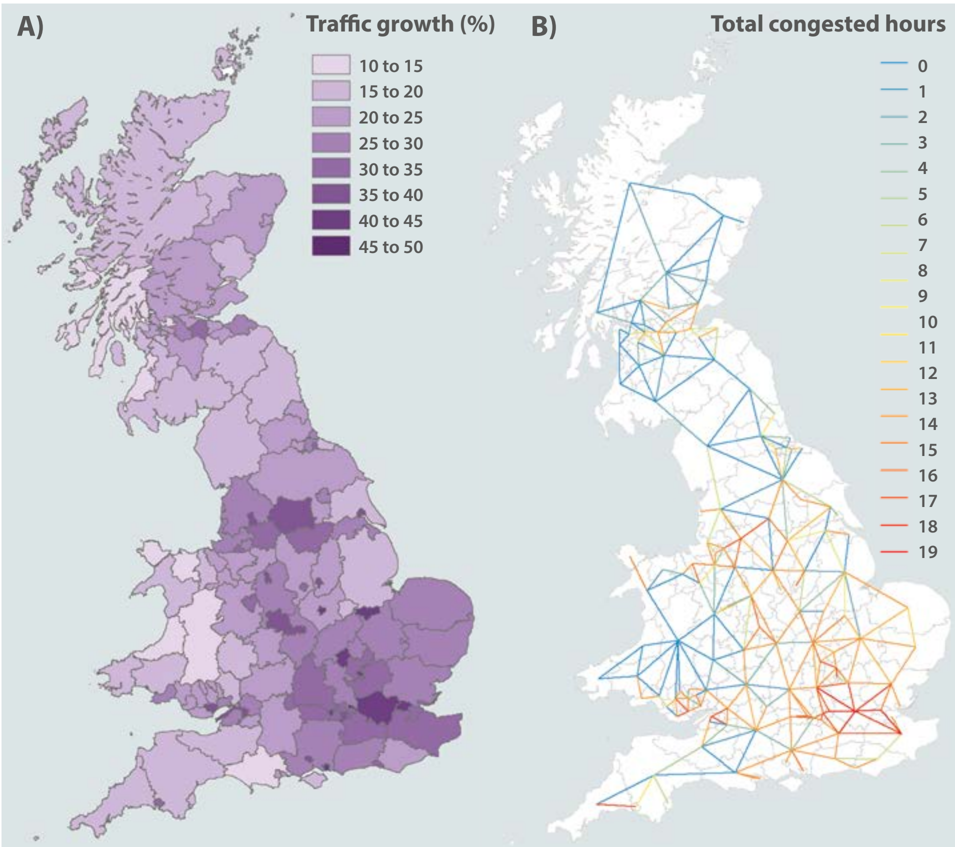


strategies TR0, TR2, TR3 and TR4. However, this strategy also assumes that technological developments such as autonomous vehicles increase the capacity of existing roads. This means that in the latter part of the century traffic levels exceed those achieved under other strategies, as exogenous growth in population and the economy outpaces the reduction in individual trip rates, and technology alleviates the capacity constraints which would otherwise have acted to limit growth. The release of latent traffic following congestion relief means that this is a possible outcome. It is also not certain that ICT improvements will lead to reductions in trip rates, and the DfT's Draft National Policy Network suggests that they are not expected to have a significant impact on travel demand (DfT, 2013).

The other exception is strategy TR6, which models a future where smarter choices are successful in encouraging people to limit car use, and innovations in urban freight provision such as freight consolidation centres and drop-off boxes reduce goods vehicle mileage. While traffic still grows, towards the end of the century it begins to plateau around 15% below the majority of strategies. This is backed up by findings from other research projects, which show that smarter choices schemes can reduce urban travel by up to 11% (Cairns *et al*., 2004), although the impact on latent traffic is less well understood.

Road Network Congestion: Figure 22A and B shows the predicted spatial variations in road traffic growth and hours of daily congestion for strategy TR0 from 2010 to 2035. This shows that there are differences in local traffic growth with the highest levels in London and in small urban unitary authorities such as Nottingham and Portsmouth, with little growth in rural authorities such as Dorset and Powys. However, traffic is predicted to grow relatively fast in some rural counties such as Norfolk. Change in traffic volume is related to spatial variations in population and economic growth, with a correlation between areas of high population and economic growth and high growth in traffic levels.

Figure 22: A) Spatial variations in traffic growth to 2035; B) Hours of daily congestion on interzonal road links in 2100 (TR0).



Further model results show both unconstrained (from strategy TR1) and constrained (from strategy TR3) road traffic on an individual interzonal link. New infrastructure from additional road lanes is constructed on each of the three road types during the study period, but while in all cases this permits a brief period of rapid traffic growth, traffic soon plateaus again at levels well below the unconstrained demand curve. This suggests that a policy of 'predict and provide' is not a sensible option for dealing with the issue of transport demand growth. It should be noted that while the traffic growth might in reality have more of a time lag than is predicted by the model, the general pattern of capacity release followed by a renewed constraint at a higher level of traffic remains valid.

Rail: Figure 23A shows predicted growth in interzonal rail traffic under the three scenarios with strategy TR0, showing that in all cases rail traffic grows throughout the study period, but that in the high and medium growth scenarios this growth is constrained towards the end of the period by increasing levels of delays. These delays result from increasingly high levels of capacity utilisation on the network, with no additional infrastructure being constructed to alleviate this congestion. As with road traffic, there is a clear link between the level of economic and population growth and the growth in traffic.

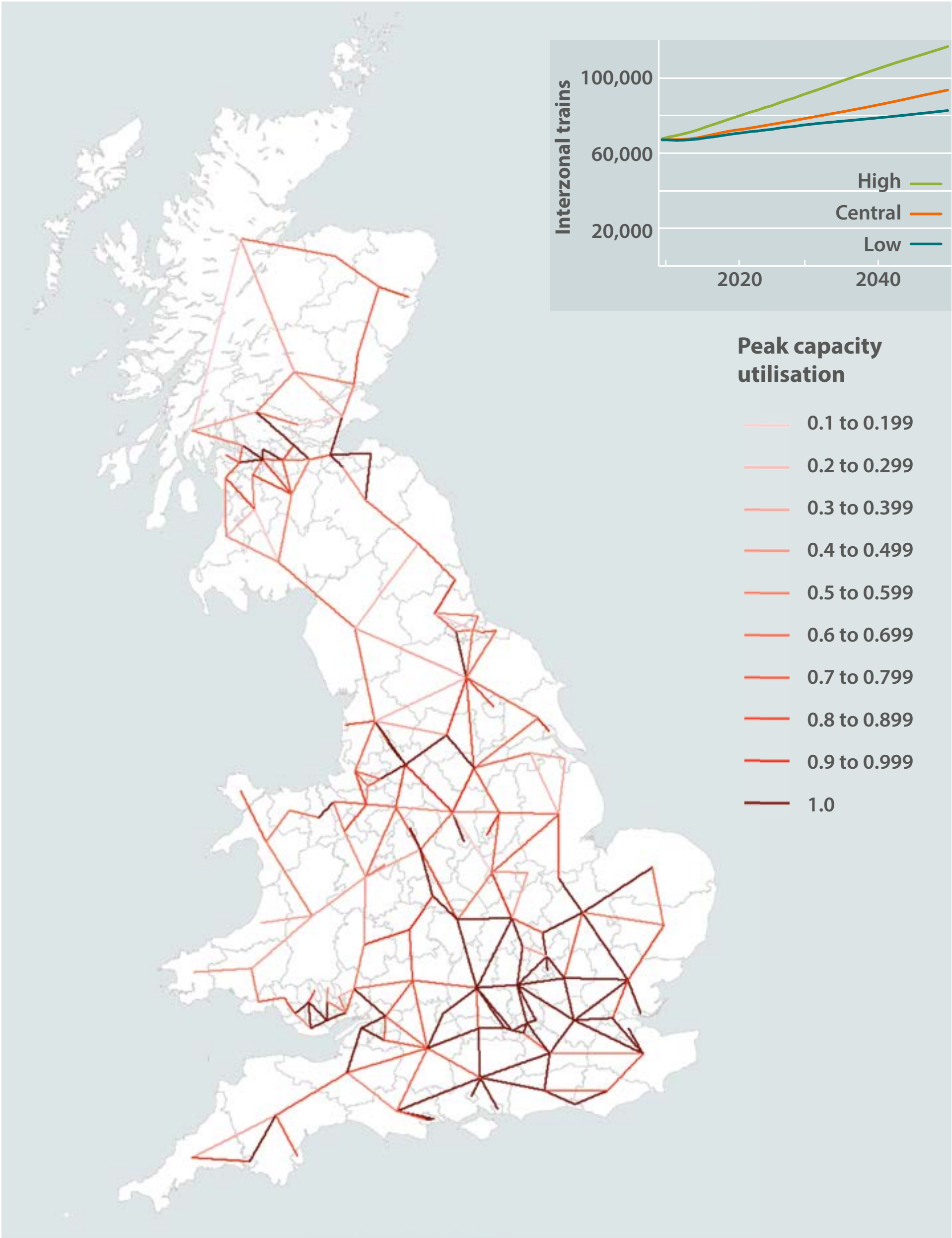
Figure 23B also shows a high degree of spatial variation in this capacity utilisation, as shown for the central scenario in 2050. Heavy congestion can clearly be seen along the southern end of the West Coast Main Line corridor, and on links radiating from Greater London, as well as in the area around Cardiff and Central Scotland. Network Modelling Framework (NMF) growth forecasts predict a 36-46% increase in passenger miles by 2030 (DfT, 2013), which would be approximately equivalent to the 'high' ITRC forecasts if this increase was proportionally reflected in the number of trains operated. In reality it would be expected that much growth would be accommodated in spare capacity on existing services or by lengthening such services, and therefore the lower ITRC forecasts are likely to provide a closer match with those from the NMF.

Air: Without further investment in airport capacity, demand for air travel initially grows very rapidly, but then plateaus as large airports become full in the second quarter of the century. Figure 24 shows that the time taken for capacity to become fully utilised varies widely between airports, with Heathrow, Gatwick and Luton becoming full up within the next decade, but with other airports such as Teesside and Inverness retaining spare capacity throughout the study period. However, it should be noted that the model treats airports as individual unlinked entities; whereas it is likely that in reality some of the demand which could not be accommodated at 'full' airports would transfer to take up the spare capacity at these quieter airports.

The volume of transfer would depend on the proximity of busier and quieter airports and the quality of the transport links between them, and might therefore be expected to be greater at quieter airports such as Teesside which are relatively close to other much busier airports. In future work the possibility of allocating a proportion of the suppressed demand from 'full' airports to neighbouring airports with spare capacity based on a distance or generalised journey cost measure will therefore be investigated.

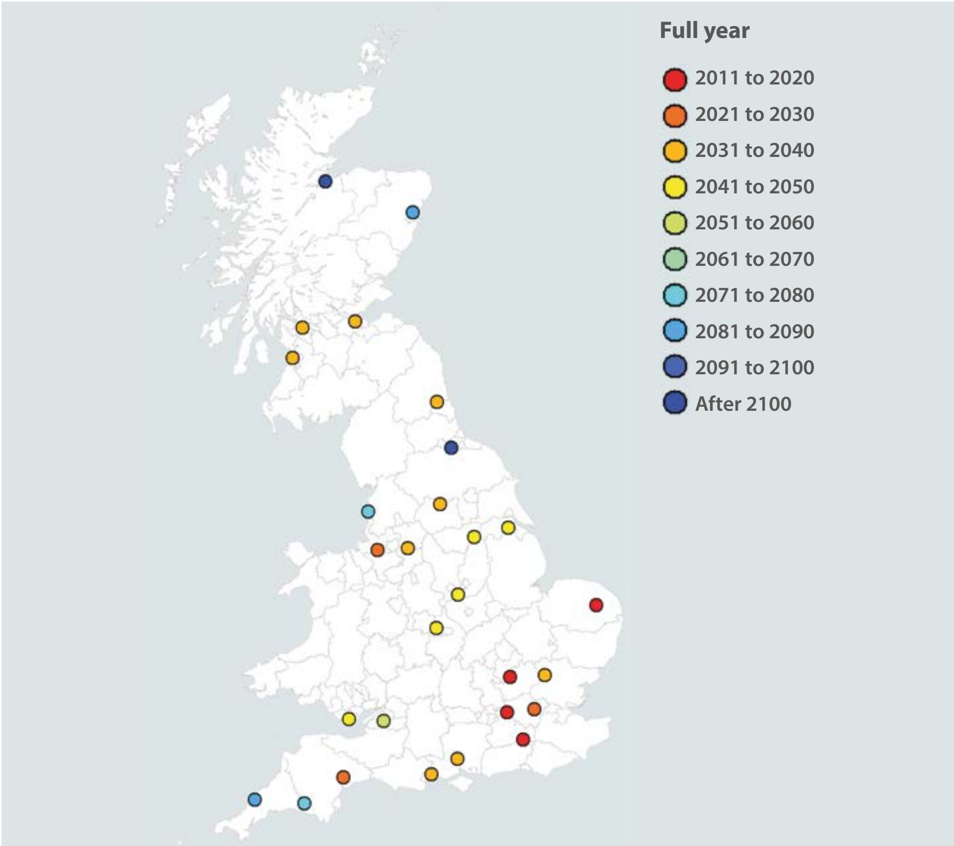
Maritime Freight: Model results indicate that baseline growth trends in total maritime freight from GB increases. However, the maritime model is currently unconstrained due to a lack of available data on port capacities, and the primary drivers for the model are population and GDP. In reality, though, there will almost certainly be economic and societal upper limits to the volume of international freight transport which will act to constrain growth. The links between the economy and freight volumes are more complex than the single elasticity approach used here, and more detailed modelling of these links will require improved data for further research.

Figure 23: A) Aggregated GB interzonal rail traffic (TR0), B) Peak interzonal rail capacity utilisation in 2100 (TR0).



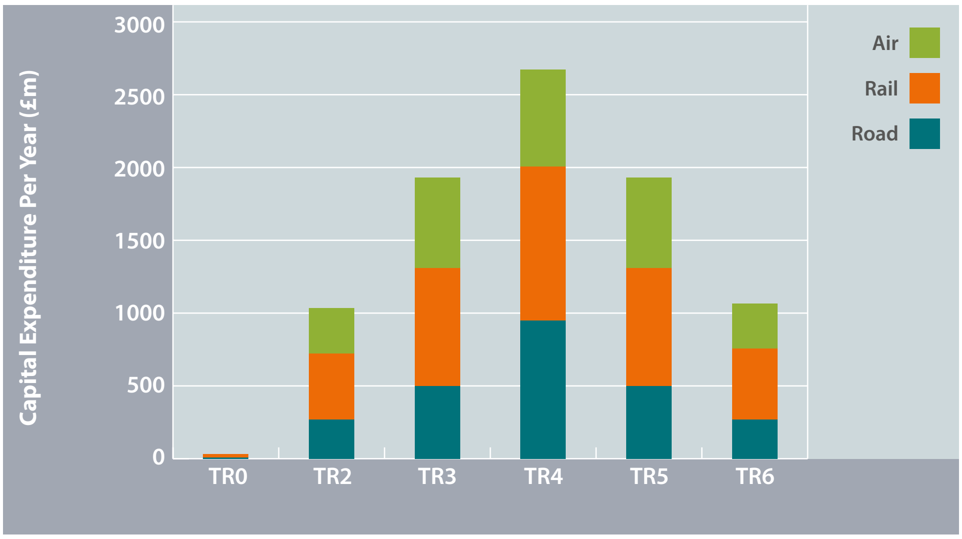
Total Investment: Figure 25 shows estimated average annual capital investment costs for six of the seven transport strategies. Strategy TR1 is omitted because the respective costs are an order of magnitude greater than for any other strategy, at over £85 billion per year. It also differs from other strategies in that the majority of capital investment goes towards airport infrastructure, followed by road infrastructure, with rail accounting for less than 10% of capital investment.

Figure 24: Decade in which UK airport capacity is reached for strategy TR0 with central case population and economic scenario input.



In contrast, the other six strategies show a relatively even balance between the sectors. The Treasury's recent report on infrastructure investment (HM Treasury, 2013a) sets out the government's plans for investment in transport over the period 2015–2021 and states that annual investment over this period will be £12.1 billion on average. However, this includes items such as local authority transport maintenance and the whole of Network Rail's direct grant which are not necessarily used for capital projects, and this figure is not therefore directly comparable with those shown in Figure 25. Nonetheless, it suggests that a strategy with investment levels somewhere between TR4 and TR1 should be considered in future work.

Figure 25: Average annual capital investment costs per strategy.



4.2.3 KEY MESSAGES

- Infrastructure capacity constraints can be a major brake on traffic growth requiring additional infrastructure. However, addressing pinch points will only provide a temporary solution, since increasing demand coupled with the release of latent traffic previously deterred by the capacity constraint means that congestion relief is likely to be short-lived. This suggests that a policy of 'predict and provide' is not a sensible option for dealing with transport demand growth.
- It is possible that peak demand effects may cause trip rate reductions due to demographic and economic change such as younger adults moving towards cities and older adults moving out, or saturation of growth in female driving license holding and car ownership. These factors along with other trends such as the relationship between vehicle speeds and constant travel time budgets, and the declining marginal utility of additional destinations, may lead to a 'peak' in road vehicle traffic (Millard-Ball & Schipper, 2010). In addition to future changes in trip rates, this phenomena means that model elasticity's may require revision over time. However, there is still debate whether 'peak demand' has actually occurred (DfT, 2013). It should also be noted that even in a scenario where individual travel has peaked, demographic changes (particularly population growth) could still lead to growth in aggregate road traffic, and could be influenced by the response of land use planning to demographic growth (Metz, 2012). As noted by the DfT (2013), housing developments, new employment opportunities and the development of other large infrastructure projects will impact on transport network use. These issues will be explored in future research potentially using a combination of NISMOD and the National Trip End Model.
- The UK is committed to significantly reducing its transport-related carbon emissions by 2050, as part of a total emissions reduction of 80% from a 1990 baseline. A policy which is likely to have an important impact on the level of transport emissions is the electrification of road transport. However this strongly depends on reducing the carbon intensity of electricity generation. While the exact pathway to electrification is still uncertain several strategies assume that this will take place to some degree over the first half of the century. This highlights a key interdependency between the energy and transport sectors discussed in Chapter 5.

4.3 WATER SUPPLY

Great Britain supports a diverse range of consumptive and non-consumptive uses for water, all of which possess stringent levels of service with respect to both water quantity and water quality dictated by a complex legislative and regulatory framework. As well as significant geographical and seasonal variability, pressures include increasing consumptive demand, an ageing and deteriorating infrastructure, affordability, and a potentially critical redistribution of resource under future climates. This provides a potent set of challenges for the water sector through the 21st century. It is unlikely that even revolutionary change in the behaviour of consumers will be sufficient to alleviate such pressures without additional investment in infrastructure. Thus, a broad programme of measures combining systematic management of supply capacity and the growth in consumptive demand across all users of the water environment is necessary.

4.3.1 APPROACH

Here we consider municipal water supply. Water supply for cooling power plants is dealt with in Chapter 5. The NISMOD model of water supply infrastructure is a daily network simulation model that represents the connectivity and behaviour of water supply infrastructure components, including reservoirs, abstractions, and water treatment works. The model compares the total demand for water services from a network with the total quantity of water available to meet that demand, subject to constraints arising from climate and weather, environmental regulation, infrastructure capacity, and infrastructure connectivity, at each component. In addition, each water supply infrastructure component has independent behaviour defined for each constraint, as well as capacity, cost, demand, greenhouse gas emission rate, and power consumption.

The effects of climate change on water resource yield are projected to vary strongly across GB and whilst some impacts may be severe there is substantial uncertainty, as they are a combined result of a number of possible changes. These include changes in seasonal mean precipitation and evapotranspiration (driven by several meteorological variables such as temperature and solar radiation) affecting long term average availability as well as more critical multi-seasonal variability causing droughts. NISMOD uses a sample of projections from the UKCP09 uncertainty ranges.

In NISMOD it is possible to investigate the impacts of a broad range of adaptation strategies on the performance of the water supply infrastructure system including the integration of existing networks, heightened constraints on abstraction, and the implementation of new sources of water. The implementation of the model used to generate pilot results comprises 11 regional water supply networks. It assumes constant capacity and greenhouse gas emission rates, but varies demand in proportion to population, and power cost in proportion to the cost of electricity. Other costs account for the change in electricity cost. The following provides interim results for the reference case strategy (WRO) using low, medium and high growth scenarios.

4.3.2 KEY RESULTS

Water demand: The per capita demand of household customers has remained fairly constant between 2005 and 2010, at between 145 and 155 l/p/d (EA, 2009b; Water UK, 2010). Between 2010 and 2011, it ranged from less than 120 l/p/d to over 160 l/p/d, with customers in the southeast of England consuming more than customers elsewhere in England and Wales (Defra, 2011).

It is widely accepted that customers whose consumption is measured using water meters consume less than those whose consumption is unmeasured. In 2008, the mean per capita demand of metered and unmetered customers in England and Wales was around 125 l/p/d and 150 l/p/d, respectively (Ofwat, 2011). Around 30% of household customers in England and Wales were metered in 2008, with the penetration of individual companies ranging from 10% to 60% (Ofwat, 2011).

Leakage: More than 4000 Ml of water are lost each day from the water supply infrastructure of GB, constituting 20%–25% of the total demand for water (Water UK, 2010; Ofwat, 2011). Individual companies' estimates of leakage having a range of over 850 Ml/d, and are differentiated by network characteristics, asset condition and consumer behaviour (Ofwat, 2011). The majority of leakage emanates from the failure of underground assets, such as distribution and supply pipe infrastructure, which deteriorate over time. To manage the risk of failure, assets are replaced or rehabilitated systematically before they fail as they age or their performance becomes unacceptable. Assets that fail unexpectedly are replaced immediately.

Although it is currently prohibitively expensive to eliminate leakage, the economic regulator provides incentives to achieve and maintain an affordable rate of investment in asset management via the definition of an 'economic' rate of leakage, below which the costs of leakage reduction exceed the benefits. Most water companies in England and Wales already maintain their infrastructure at this level, about 20% of the total water input to supply; however, the regulator anticipates a further 2% reduction in the national aggregate level of leakage between 2010 and 2015, with some companies expected to reduce leakage by as much as 7% over this period (EA, 2009b; Ofwat, 2009).

In Scotland, where the current rate of leakage greatly exceeds that of England and Wales, Scottish Water anticipates a reduction of 50% for the same period (Scottish Water, 2011). Between 2002 and 2010, the water industry invested around £2 billion annually in asset replacement, corresponding to an annual reduction in leakage of just over 105 Ml/d, or an annual decrease of around 2% (Water UK, 2010).

Water supply: Estimation of the capacity of the public water supply is complex. It exhibits large variation across water suppliers and is dependent on a number of factors, including climate, land-use and management practices. The amount of water available to meet demand in England and Wales was 17,016 Ml/d in 2010–2011 (Ofwat, 2011); the combined yield of all sources in Scotland was 3564 Ml/d in 2001 (Scottish Executive, 2003). These quantities may have slightly differing definitions; however, we assume no discernible difference between deployable output and the water available to meet demand. Thus, the combined water resource of Great Britain is 20,580 Ml/d, which is adequate for an aggregate 2008 baseline value.

In the absence of active intervention, the combined effects of population increase and climate change represent a strategic challenge for the UK water industry (Figure 26), representing a progressive erosion of security of supply. Figure 26 masks considerable regional variation, though our model results are not yet sufficiently robust to report at the regional scale.

Table 4 summarises the decade in which demand may exceed capacity when accounting for the impact of climate change. It underlines that the high demand scenario places significant strain on the water resource infrastructure, and also suggests that the medium and even low growth scenarios may overwhelm national capacity.

Figure 26: Municipal water supply capacity and demand in Britain under low, medium and high growth scenarios and low, central and high climate scenarios.

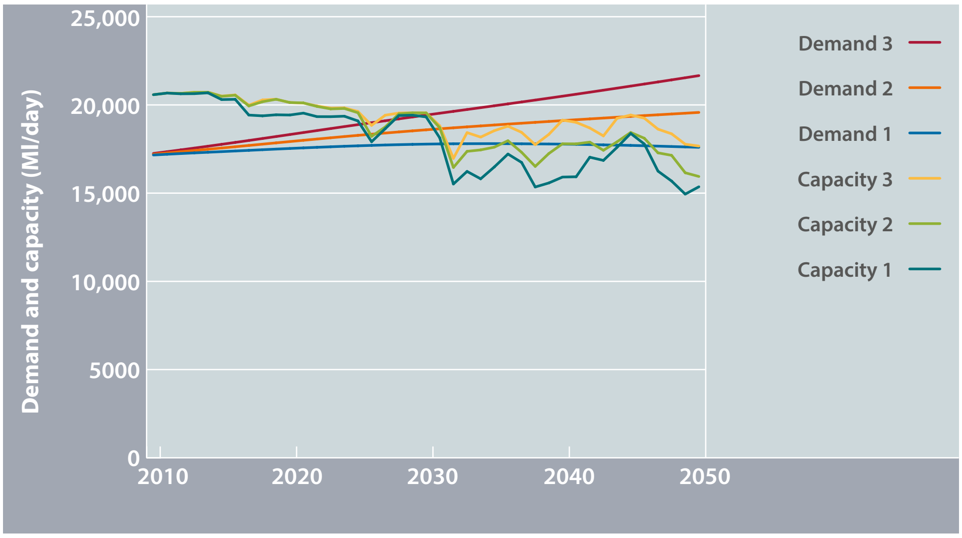


Table 4: Decade in which demand exceeds supply, averaged across Britain. Baseline investment scenario.				
		Low	Central	High
Demand scenario	Low growth		2040s	2020s
	Medium growth		2030s	2020s
	High growth	2030s	2020s	2020s

Analysis of capacity at the resolution of regional sub-networks indicates substantial variability between regions.

Strategies for water supply: Analysis of strategies for water supply is still in progress.

4.3.3 KEY MESSAGES

- The impacts of climate change are highly uncertain but of great significance for water supply infrastructure.
- Increasing demand for water due to population pressure coincides with locations in the South-east of England that are also resource constrained. However, resource constraints are not isolated in the South-east, with catchments elsewhere at risk of over-abstraction.
- Demand reduction has the potential to significantly delay the timescale over which investments in new capacity are required.
- Our modelling of strategic responses to water resource constraints is not yet complete.

4.4 WASTE WATER

Today there are over 347,000 km of sewers collecting over 11 billion litres of wastewater every day. There has been extensive investment in wastewater treatment in order to improve water quality standards in rivers and coastal waters, though improved treatment standards have raised energy costs. Energy use in wastewater treatment now averages roughly 300 MW. Both sewage treatment and sewerage are capital intensive, with a long design life ranging from 40–100 years. Options that would reduce or eliminate energy input to wastewater treatment are needed to ensure the future affordability of service. Projected changes in rainfall patterns due to climate change and major and minor flooding pose a risk to the existing drainage infrastructure.

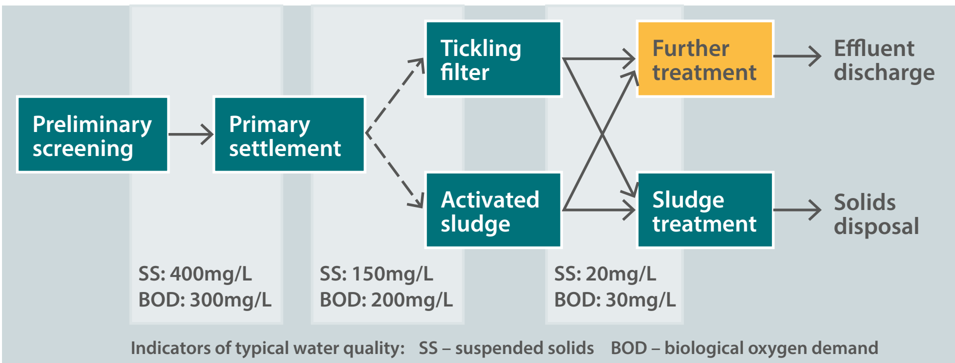
It is vital to maintain collection and treatment of wastewater; so the key driver of provision is population demand. In addition, pressures from increasing population will necessitate ever higher standards of treatment to maintain water quality in our water bodies.

The sewer network represents approximately 60% of the total asset value of the water industry. However, much of the network dates back to the late 19th century and earlier. Replacement programs are expensive, and there is little incentive to do so for pipelines carrying a low-value product, so much of the network continues to age. In addition, urban runoff is also directed to the sewerage system, with the result that the collection and treatment systems become overloaded during periods of intense rainfall. The use of sustainable urban drainage systems provides a means of limiting the increase in water volume entering the system due to population increase and associated building construction.

The aim of sewage treatment is to remove unwanted compounds from the wastewater, in order that the treated effluent can safely be returned to a river, lake or the sea. This does not necessarily involve sterilization, but rather reduction of the levels of contaminants and nutrients in the wastewater, to a level where the chemistry and ecology of the receiving water body is not significantly disturbed. The level of these contaminants in the effluent is closely monitored, and is dependent on the environmental sensitivity of the receiving water body.

Separation of the water and contaminants is performed in a number of stages (Figure 27) leading to increasing water quality, the most basic of which is the mechanical screening of the waste for solid matter, followed by sedimentation.

Figure 27: Schematic of current common practice in sewerage treatment.



Two alternative processes are currently used for secondary treatment of wastewater in Britain, both relying on populations of bacteria to break down the organic nutrients in the wastewater. The first is the activated sludge process, where the wastewater is aerated mechanically, and the second is the fixed filter or trickling filter process, where the wastewater is passed slowly through a porous medium affording maximum surface area to support the bacteria population. The activated sludge process is extremely expensive in energy, while the fixed biofilm process requires a large area of land to house the tanks. As a result of this, smaller processing plant tends to use the fixed biofilm process, while plant serving large communities almost exclusively uses the activated sludge process. It should be noted that the higher the standard of output required, the longer the secondary processing needs to take; necessitating higher tank capacity and energy use to serve the same population.

Aerobic processes such as activated sludge or fixed biofilm produce as a by-product a large quantity of sludge, formed of debris from broken down cell matter. This can either be disposed of to landfill, or it can be processed in a number of ways to enable safe disposal. After further drying, it can be sterilised to spread on land as a soil conditioner, or incinerated to produce energy, or digested aerobically to provide methane, which can also be used to give energy.

The design life of a sewage processing plant is approximately 50 years for the civil engineering and 20 years for the mechanical and electrical equipment. In addition, current processing is extremely expensive to run in terms of power requirement. However the capital expense of plant replacement is so high that newer, cheaper processing technology will only be adopted if a clear and rapid return can be seen in running costs. The most likely opportunities for introduction of new technology come with replacement of aging plant or with population increase.

4.4.1 APPROACH

Future development options for sewage treatment fall into three groups (Figure 28):

a. incremental, where upgrade is made piecemeal in reaction to pressures from legislation and increasing population;

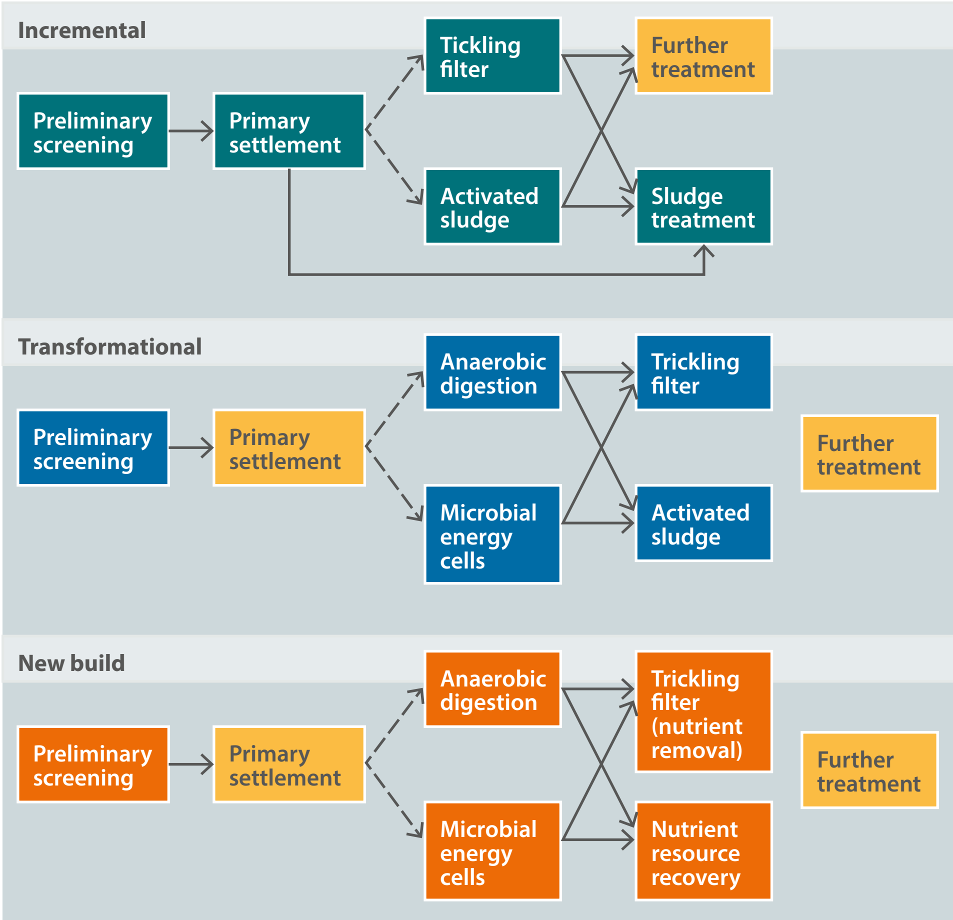
b. transformational, where the configuration of processing is changed at opportune times using new technology, leading to reduced energy usage and increased processing quality; and

c. New build, allowing for maximum recovery of the valuable materials and energy in our wastewater.

Incremental development would involve upgrading installations and equipment in response to population growth and plant senescence. Energy expense of processing could be offset still further than at present by the increase of anaerobic sludge processing, which currently provides 70MW of energy. As many pollutants as possible should be tackled at source; the water industry is already encouraging the farming community to reduce nutrients in farm runoff, as is the Environment Agency.

Transformational development would involve the introduction of either microbial energy cells or low temperature anaerobic digestion as first pass processing, harvesting the energy potential of the wastewater, dramatically reducing the sludge, and forming a pre-processing for the more conventional aerobic processes, enabling them to be more effective for a lower cost. The juxtaposition of these different processing technologies, involving different populations of bacteria, increases the effectiveness of processing a wide range of pollutants. This is especially important as new pollutants become apparent; a current example is the presence of oestrogen-like compounds, where minute concentrations can have a significant

Figure 28: Schematic of potential future sewage treatment pathways.



effect on aquatic life, but whose removal is extremely expensive in both cost and energy with current processing configurations.

While the use of anaerobic digestion for raw wastewater is well established in warmer climates, to date anaerobic digestion in this country involves pre-heating the influent. However low temperature digestion of raw wastewater has been demonstrated at laboratory scale, producing equivalent volumes of methane to the existing operational plants, although at a slower rate. Microbial fuel cells have been demonstrated as a pilot plant, but to date, the quantity of hydrogen produced is not enough to do more than recover the processing energy.

The new build option involves the recovery of the useful materials in the wastewater. This is already being done in some places, for example by recovering phosphorus and ammonium for fertilisers, however with the introduction of microbial fuel cells, the range and value of output products can be substantially increased.

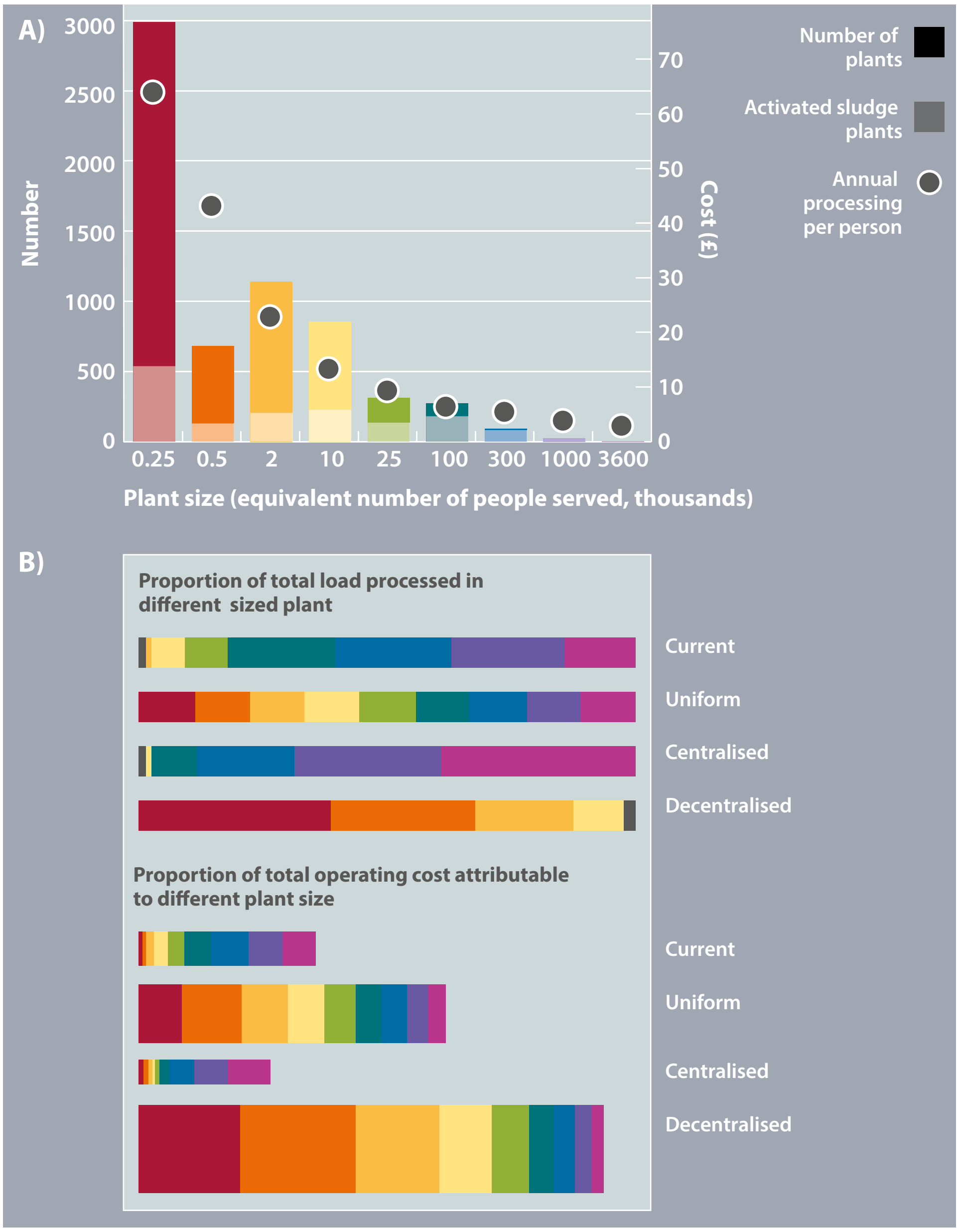
While the first of these development options can be evaluated, the second is at laboratory or pilot stage, while the third involves technologies that have yet to be developed. Thus the only option which can be effectively modelled is the first. The model description of wastewater treatment is an annual economic model intended to demonstrate the effect of increasing population and energy costs on the cost of processing. Starting from the current distribution of sewage treatment works, these are augmented as their catchment population increases. No allowance is made for increased processing quality as the plant size increases.

Results are provided for the WR0 – Current Trend strategy using 3 (scenario d, a, f) scenario inputs corresponding to high, central and low population/economic growth projections. See Appendix 1 for strategy narratives.

4.4.2 KEY RESULTS

Figure 29(a) shows the current distribution by size of sewage treatment works in Britain, together with the per capita waste processing cost in each plant size. A clear economy of scale is seen. Figure 29(b) shows the effect of different distributions of plant size on the overall treatment cost. While it would seem clear that reduction of the number of sewage treatment plants would be advantageous, the break-even time of amalgamation of two sewage treatment plants is such that it is not economically viable to centralise treatment merely for the purposes of reducing operating costs. However, plant can be amalgamated when increasing capacity or undertaking upgrades. The drawback to this strategy is the limitation in the effluent load sustainable by the receiving water body. A requirement for higher effluent quality demands higher energy input, and shows a less marked economy of scale both in infrastructure and in processing cost.

Figure 29: A) Current distribution of sewage treatment plant size, together with the cost of processing per person. B) Effect of different plant sizes on total operating costs.



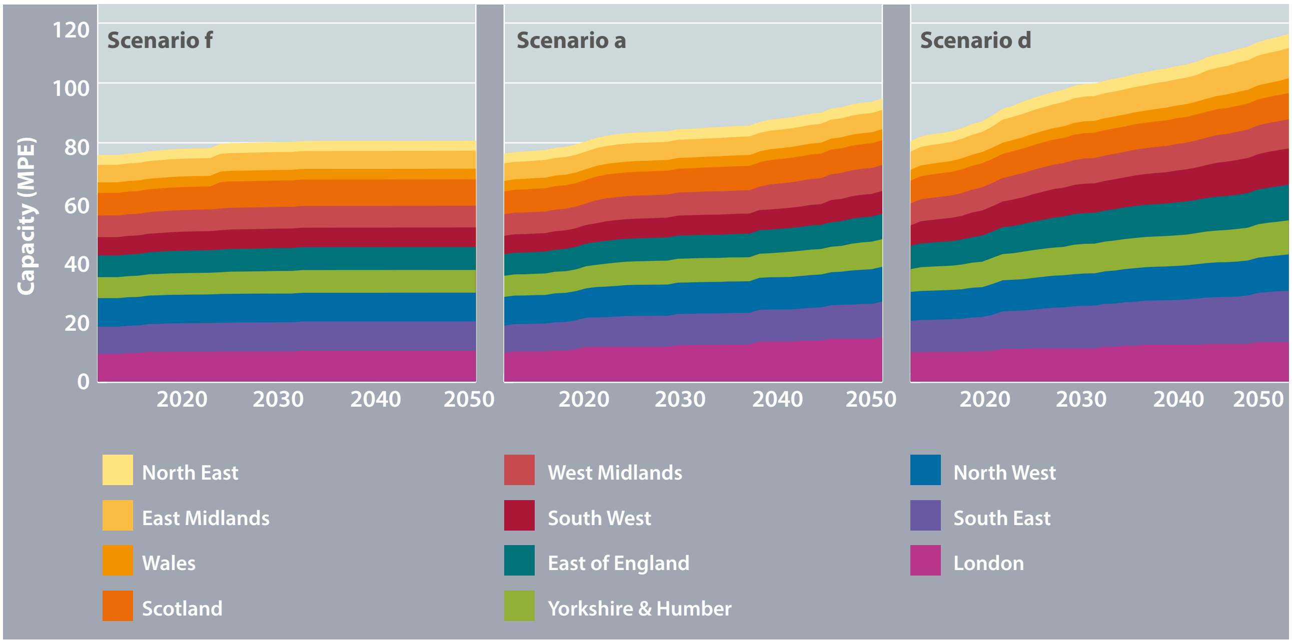


Figure 30: Growth of sewage treatment capacity with projected population increase.

Figure 30 shows the projected growth of sewage treatment capacity with population increase. The result of this increase is that the size of the plants grow; however in reality savings arising from economies of scale may be undermined by the necessity of increasing effluent quality in the face of higher effluent volume.

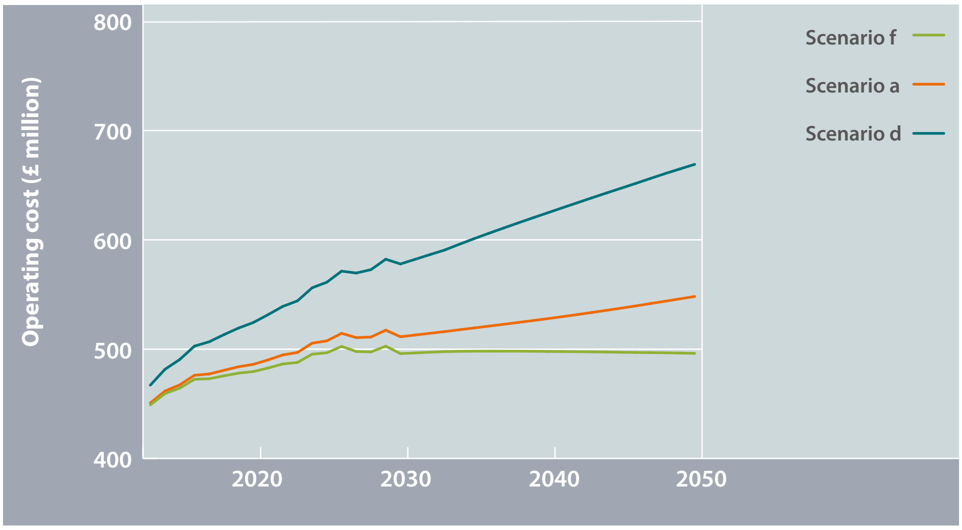


Figure 31: Annual sewage treatment operating costs under different population growth scenarios.

Figure 31 shows projections for the increase in operating costs of sewage treatment works in Briatain. Since the dominating element in these operating costs is energy exenditure, it can be seen that the use of energy for sewage treatment can be expected to grow rapidly during the 21st century under this incrementalstrategy, in spite of proportionally increasing power generation from anaerobic sludge digestion.

Figure 32 shows projected cumulative capital expenditure, which is still greater than the operating expenditure. It should be noted that this does not include the capital cost of replacing ageing plant, nor does it include the cost of augmenting and repairing sewers. At the current time, the total capital expenditure on sewage treatment works and on augmenting and repairing sewers is approximately 4 times as great as the cost of increasing treatment plant capacity.

In addition to any results on capacity and quality increase in sewage treatment, the replacement cost of the sewer network, at approximately £200bn is substantially higher than that of the treatment plant. Although programmes exist for the inspection of critical sewers, those with the highest economic consequences of failure, a replacement programme for the entire network is not in place. Allowing for an effective life of 100 years would require annual replacement expenditures of £2bn, and would be greater than treatment plant expansion costs.

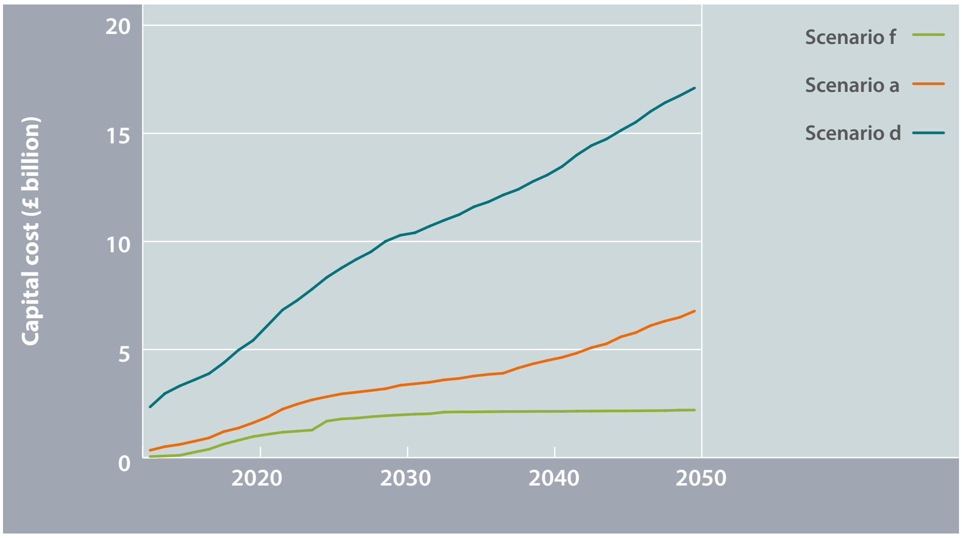


Figure 32: Cumulative capital expenditure on increasing sewage treatment capacity under different population growth scenarios.

4.4.3 KEY MESSAGES

- Continuing with current processing technology will be extremely expensive in terms of both cost and emissions. New technology and processing configurations are needed to reduce the energy required in processing.
- Based on interim results it does not seem that a consistent decentralisation policy in sewage treatment is currently effective.
- A systematic programme of sewer replacement would add a substantial cost to the capital expenditure on infrastructure.

4.5 SOLID WASTE

The UK solid waste sector deals with approximately 300 million tonnes of waste annually. In the last decade, the sector has transformed rapidly, responding to EU and national legislation. This has increased the amount of waste recycled, composted or reused and nearly halved waste going to landfill. Historically, economic growth and household waste generation were coupled, but there is some evidence that this may no longer be true. National and EU directives for reducing solid waste (e.g. possible banning of all biodegradable municipal waste to landfill in the next decade) will affect the levels of investment needed in the near term. There is the possibility of a complete paradigm shift towards solid waste becoming a resource recovery industry.

The solid waste infrastructure system covers both waste gong to landfill and resource management whereby resources are reclaimed by recycling and processing. The infrastructure comprises (i) transfer stations for sorting, recovering and consolidating waste prior to onward processing or disposal; (ii) material recovery facilities (MRFs), where waste is sorted prior to transport for recycling; (iii) recycling or other processing facilities (e.g. anaerobic digestion); (iv) landfill and (v) incinerators, where waste is combusted usually to produce electricity. There are three main sub-systems: collection, treatment and final disposal.

Waste tends to be categorised by generating sector: household waste (collected from the kerbside or taken to a 'bring site' (e.g. bottle or textile bank) or Household Waste Recycling Centre (HWRC)); commercial and industrial (C&I); construction and demolition (C&D); mining and quarrying; and agricultural. Hazardous waste is categorised separately.

4.5.1 APPROACH

NISMOD assesses the solid waste demand and capacity balance at a government office region scale. The solid waste analysis models capacity and demand for 4 waste sources: municipal solid waste (MSW), commercial and industrial waste (C&I), construction and demolition wastes (C&D) and hazardous waste. The model forecasts change in demand and capacity utilisation in yearly intervals from 2011 to 2100 but currently presents results to 2050. This is based on changes in regional population and GVA and energy costs. The solid waste model uses the same economic and demographic input data as the other sectors representing a high (Scenario 3), central (Scenario 2) and low (Scenario 1) population growth. The strategy analysis uses Scenario 2 as the baseline population growth projection, while the others scenarios are presented to indicate high and low sensitivities for strategy results. The strategies modelled are:

- WE0: Business as usual
- WE1: High tech
- WE3: Deep green

See Appendix 1 for strategy narratives.

Until recently MSW was defined as waste collected by local authorities (Local Authority Collected Waste (LACW)). However, in 2010 (in response to EU reporting requirements for waste arisings) this was redefined to include some biodegradable content of the C&I waste stream; MSW arisings under the new definition have roughly doubled. Waste may be transported to large-scale waste treatment facilities for processing. The number of transfer stations and processing facilities used in the recovery of recyclables from waste has increased over recent years in England and Wales from 950 in 2007 (EA 2007) to 1380 in 2009 (EA 2009a). The most common waste treatment facilities are:

- *Materials Recycling Facilities (MRFs)* – of two types – dirty (i.e. black bag MSW) and clean (dry co-mingled recyclables). In both cases, the mixed waste is mechanically- and/or hand-sorted. Outputs include recyclable fractions including paper, cardboard and metals. The non-recyclable residue may be sent for further processing, e.g. in-vessel composting (IVC), used as refuse derived fuel (RDF), recovered to land (i.e. used to replace fertilisers for soil improvement), or sent to landfill.
- *Mechanical Biological Treatment Facilities (MBT)* – an extended MRF with an anaerobic or aerobic biological treatment stage to reduce the biodegradability of residual material. Outputs include recyclables, treated residual waste which may go to landfill, and sometimes solid recovered fuels (SRF).
- *Composting Facilities* – large-scale open windrows treating garden waste or in-vessel composting (IVC) for food and green waste. Outputs include mature compost which may be used for soil improvement, the nature of which depends on the waste stream and the treatment process.
- *Anaerobic digestion plants (AD)* – to treat food and green wastes. Outputs include digestate (which may be used for soil improvement), biogas (fuel) and non-fossil CO_2. The biogas is typically combusted on site to produce electricity and/or heat.
- *Energy from Waste (EfW)* – primarily incineration plants (AD is technically included in this broad terminology but often referred to separately as it is here). These may be combined with an MRF to recover recyclables prior to incineration. Outputs include electricity (& heat), recyclables, aggregate and ash as well as CO_2 and nitrous oxides.

The following technologies are relatively new to the UK market:

- *Mechanical Heat Treatment Facilities (MHT)* – an MRF where the mixed residual waste is heat treated for sanitisation. Outputs include recyclables, SRF and a residual waste fraction to landfill.
- *Gasification* – an advanced thermal treatment process, which may be combined with an MRF to recover recyclables prior to gasification. Outputs include syngas (mainly CO and H2) that is usually combusted on site to generate electricity (& heat), recyclables (if coupled with a MRF), slag and ash.
- *Pyrolysis* – an advanced thermal treatment process, which may be combined with an MRF to recover recyclables prior to treatment or use SRF as the feedstock. Waste is heated to high temperatures in the absence of oxygen. Outputs may include char (a carbon-rich solid fuel), liquid or gaseous fuels depending on processing temperature (Williams and Barton 2011), recyclables and ash as well as CO_2 and nitrous oxides.
- *Plasma arc gasification* – an advanced thermal treatment process, which may be combined with an MRF to recover recyclables prior to treatment or use SRF as a feedstock. Waste is heated in a low oxygen atmosphere using a plasma torch. Outputs include syngas which maybe combusted on site to produce electricity (& heat), recyclables (if combined with an MRF) and vitrified slag.

4.5.2 KEY RESULTS

Total Waste Arisings: The arisings for MSW (new definition) in England are shown in Figure 33. The strategies used are WE0 (Business as usual), WE1 (High tech) and WE3 (Deep green) with the waste arisings coupling factor taken to reduce annually at 2%, 1% and 4% respectively. When disaggregating these results into three English Government regions –

Northwest, Yorkshire and Humberside and Eastern, the residual waste treatment capacity is sufficient until the early 2020s for all scenarios, except for the Eastern region, which has a capacity shortfall in High tech scenario 1. In the Northwest and Yorkshire and Humberside, there is no longer sufficient capacity for any of the high tech strategy scenarios after 2027 (2022 in Eastern). There is sufficient capacity to deal with all the remaining scenarios until 2035 in the Northwest and Yorkshire & Humberside.

In the Northeast, the capacity of the existing and consented residual waste treatment facilities (excluding landfill) exceed the projected residual waste arisings within the region by 2020, meaning it has spare capacity that may enable other regions to meet their 2020 targets (although with potentially high transport costs). There is excess capacity in this region in all scenarios and strategies until 2038 and in all growth scenarios for the Business as Usual and Deep Green strategies until 2090.

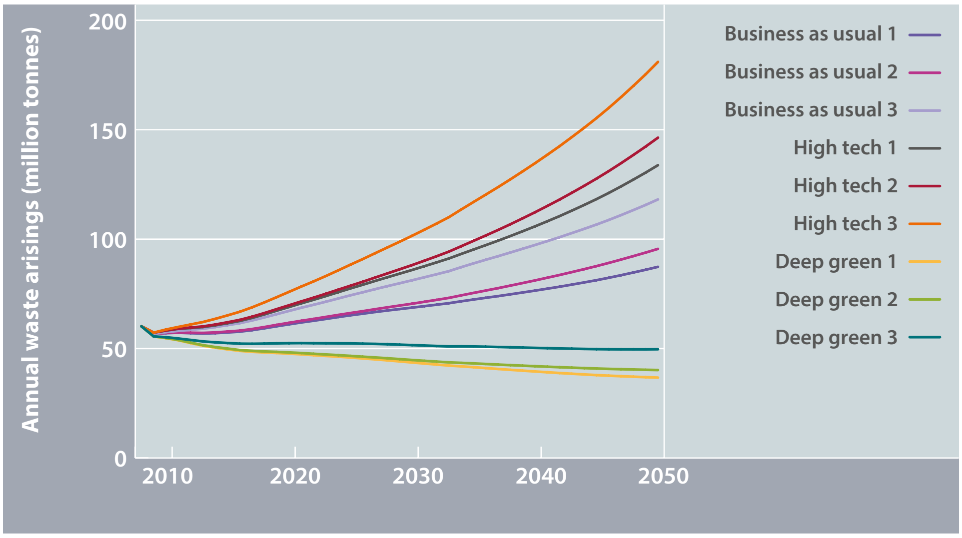


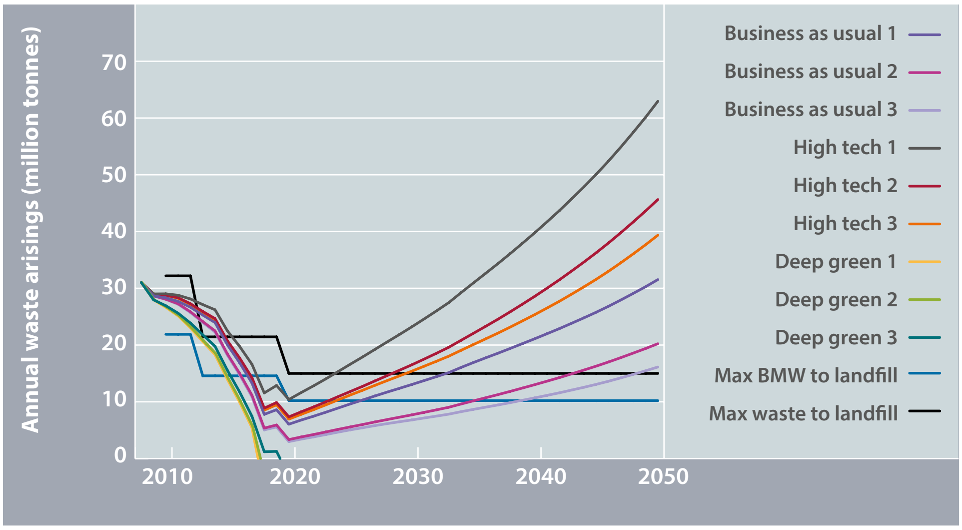
Figure 33: MSW (new definition) arisings for England.

In the remaining five government regions, Southeast, Southwest, London, West Midlands and East Midlands, the capacities of the existing and consented residual waste treatment facilities (excluding landfill) are, in most cases, insufficient to deal with any scenario and strategy combination until mid-century when the Deep Green scenarios 2 and 3 have led to sufficient per capita waste reductions that, coupled with low economic and population growth, there is sufficient residual waste capacity. The gap between the residual waste arisings and the treatment capacity will need to be filled by landfill. However it should be noted that in England and hence in some or all of the regions, the 2013 biodegradable municipal waste (BMW) diversion and recycling and composting targets were met in 2010, showing that the recycling and composting targets were exceeded rather than just met.

Landfill Requirements: Figure 34 shows the landfill requirements for English MSW until 2050. The landfill requirement is taken as the regional MSW arisings, less the recycling and composting target and residual waste capacity. It is assumed that transportation between the regions is allowed such that any excess residual waste treatment capacity is used to process the waste from regions with a capacity shortfall.

These results indicate that 1) The scenarios and strategies modelled all enable the limits on biodegradable municipal waste (BMW) disposed of to landfill set out in the Landfill Directive to be met; 2) The high tech strategy (in this instance the coupled growth is modelled but the increase in recycling and other treatments have not been) leads to huge increases the capacity of all waste treatment types needed to avoid fines from the EU for failing to comply with the Landfill Directive; 3) It is much more effective to reduce waste arisings so that less infrastructure is required, than to try and build extra capacity.

Figure 34: The English requirement for MSW landfill with inter-regional transport such that any spare residual waste treatment capacity in a region is used by regions with under-capacity.



Capacity Shortfall and Investment: Figure 35 shows the capacity shortfalls in England for Scenario 2 and the Business as Usual, Deep Green and High Tech strategies, assuming inter-regional transport is allowed. Figure 36 shows the associated investment costs. These figures show that it is much more cost effective to add recycling and composting capacity than to add residual treatment capacity but in order to be able to do this it is necessary to change behaviour.

Figure 35: Shows the assumed shortfall in recycling & composting capacity and residual waste treatment capacity in England (see text for details of the assumptions made in the calculations), for Scenario 2 for each strategy and each growth scenario with inter-regional transport.

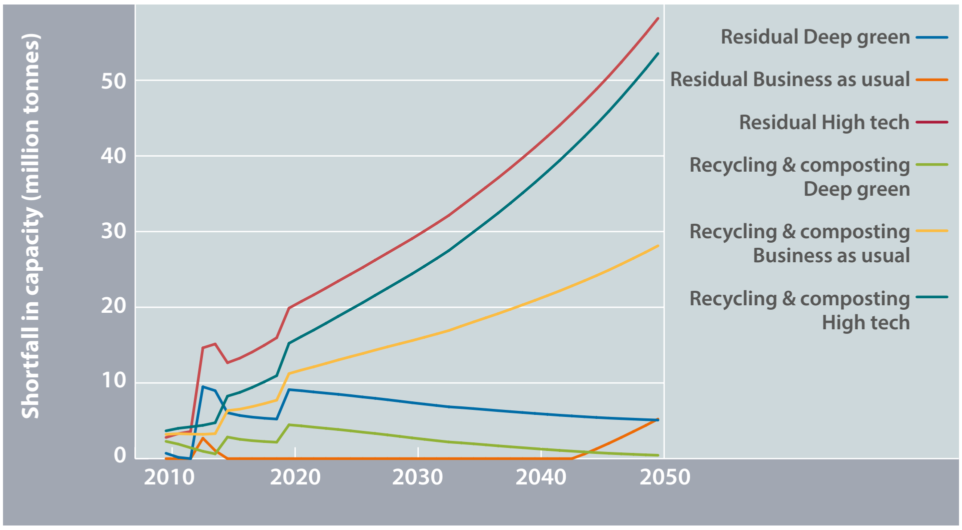
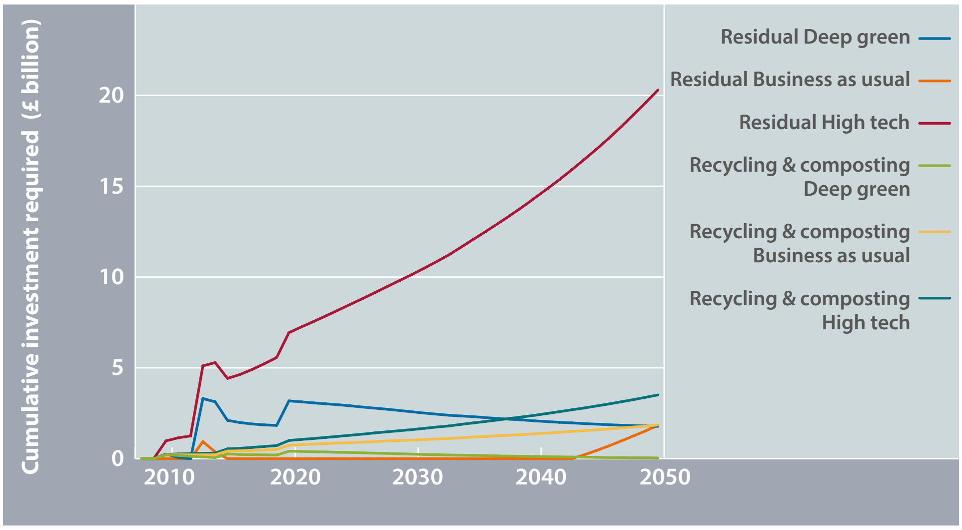


Figure 36: Costs associated with the capacity shortfalls shown in Figure 35.



4.5.3 KEY MESSAGES

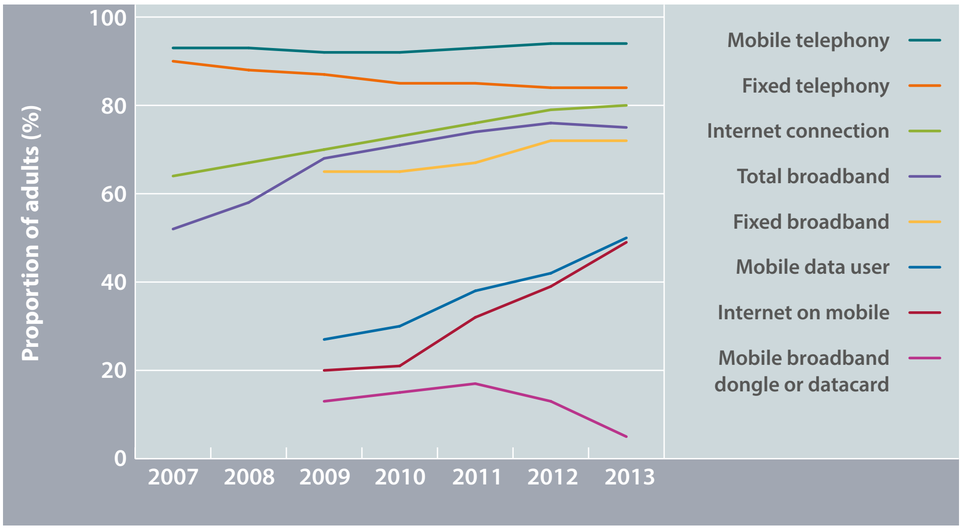
An important finding is that it is more effective to reduce waste arisings so that less infrastructure is required, than to try and build extra capacity. This point is illustrated by further analysis of English landfill requirement if we assume that the recycling and composting rate rises at 1% a year until it reaches 75% and then remains at this level. This significantly reduces the impact of the waste growth rate in the high tech strategy, but the consequence is that this requires recycling and composting over 135 million tonnes of waste per annum by 2050 under the high growth scenario coupled with the high tech strategy. Even in the lowest growth scenario, the high tech strategy still requires capacity to recycle, compost or reuse 100 million tonnes of waste per annum by 2050.

4.6 INFORMATION AND COMMUNICATION TECHNOLOGIES

In comparison to the physical infrastructure sectors already discussed, ICT is a new and rapidly changing sector, but it is less clearly defined and understood. ICT infrastructure is considered to comprise communication (including fixed and mobile telephony, broadband, television and navigation systems) and computation (including data and processing hubs) systems. Significant increases in ICT capacity have been provided via a competitive industry, which has innovated to provide new technologies and respond to consumer demand (which is itself largely driven by innovations in consumer technologies and business practices). Further rapid increases in coverage, in particular in superfast broadband, are anticipated, though there are some locations where the market alone cannot deliver. Use of the electro-magnetic spectrum may also become a constraint without spectrum reallocation and technological solutions to support more efficient use of existing spectrum.

The increased integration of information and communication technologies in recent decades has seen the ICT sector emerge as one of the most rapidly changing infrastructure sectors. Globally, this sector serves 2.7 billion Internet users amounting to 40% of the world's population (ITU, 2013a). In the UK this sector serves over 21.7 million broadband subscriptions (over 80% of households) and more than 82.7 million mobile phone subscriptions (94% of adults) (see Figure 37 Ofcom, 2013b). The UK is ranked 8th on the global ICT Development Index (ITU, 2013b) and must continue to maintain its global competitiveness in this key sector, especially with a national economy dominated by the service sector.

Figure 37: Household take-up of communications services (Ofcom 2013a).



4.6.1 FUTURE DEMAND

For mobile broadband, there is a need for capacity enhancement in the coming decades due to growing demand. This is driven by the non-uniformity of traffic between users, different locations and the time of day (Real Wireless, 2012). This capacity enhancement will need to feature new technological innovations in spectrum efficiency (including via LTE-Advanced and its evolutions) at existing cell sites, as well as the inclusion of additional antennas in both base stations and mobile devices.

Current demand for Very High Bandwidth Connectivity (VHBC) services is driven by the substantial volumes of data recorded from large numbers of customer transactions, financial trading and intensive use of imaging and video data (CSMG, 2013). This is in addition to the increasing use of remote, off-site data centre services and cloud computing. Certain sectors of the economy are driving this increase. This includes the growth in trading volumes in the financial services industry, the desire for richer content and HD video in media, the aggregation of large numbers of CCTV channels to prevent fraud and theft, and more data intensive research programmes in higher education and research.

In the retail market, while over half of the UK's population has access to super-fast broadband, there continues to be problems for consumers living far away from the telephone exchange (Ofcom, 2010). The failure for ISPs to achieve the economies of scale necessary for investment, limits the access speeds that many consumers obtain. To overcome this market failure, Broadband Delivery UK is the delivery agency created primarily, but not exclusively, to improve high-speed access in rural communities (DCMS, 2013).

Based on current trends and an analysis of devices and user mobility, Real Wireless (2012) have projected that demand for mobile broadband may grow between 23 and 297 times over the period 2012-2030, with 80 fold increase being the mid case scenario. Given this plausible range of outcomes, there is a need to meet demand by securing new spectrum options for enhanced capacity.

4.6.2 CAPACITY INVESTMENT

Currently more than 73% of UK populations have access to the Internet (ONS, 2013). The UK governments have rolled out plans to enable all households to have access to Internet by 2015 (DCMS, 2013). According to Ofcom, 4G coverage is planned to be available to 98% of the UK population and business which will enable them to experience higher broadband speed to surf and download (Ofcom, 2013b). Ofcom's targets say that 4G must reach 98% of the population and 95% of the country by the end of 2017.

The availability and increased penetration of faster broadband speeds has been estimated to add £17 billion to the UK's annual GVA output by 2024, an increase of 0.07% (SQW, 2013). The UK's current set of publicly funded broadband interventions has been estimated to contribute £6.3 billion to this GVA increase, producing a return of roughly £20 in net economic impact for every £1 of public investment (Ibid.).

Traffic statistics over the London Internet Exchange's (LINX) network routers, which interconnect the UK's Internet Service Providers (ISPs), show that data traffic has increased by more than six times since 2008 (London Internet Exchange, 2013). Conservative traffic estimates show that in 2013 over 1 terabyte of traffic was exchanged per second between ISPs. Modern technologies, such as wavelength-division multiplexing (WDM), have enabled ISPs and other Very High Bandwidth Connectivity (VHBC) users to multiply by several times the bandwidth transmissible in communications networks (e.g. over fibre), without necessarily expanding the physical network infrastructure.

In recent years, commercial operators in the UK have begun to deliver Next Generation Access (NGA) super-fast broadband services (>24Mbps) to the UK market. This capacity expansion relies on the replacement of traditional copper or coaxial cable with fibre optic cable, between the telephone exchange and the final consumer. Over 90% of premises in the UK's largest cities have access to NGA services (Analysys Mason, 2013). Ofcom (2010) has been concerned that the increasing number of consumers utilising broadband connections for information intensive activities is starting to limit the capacity of current communications networks.

The estimated cost of rolling out fibre nationwide ranges from £5.1 – 28.8 billion depending on the technology used (Analysys Mason, 2008). The cheapest option at £5.1 billion is Fibre To The Cabinet (FTTC), whereas Fibre To The Home (FTTH) costs five times greater with the costs of deploying fibre in rural areas far exceeds the costs in urban areas. This level of ICT infrastructure investment can subsequently impact on jobs, productivity, competitiveness and quality of life. Research examining the employment effects of investment in the UK's ICT infrastructure found that spurring £15 billion of additional investment would create approximately 700,000 jobs (Liebenau *et al*. 2009). Of these jobs, 360,000 would be in small businesses. Although the report does not advocate a specific level of investment, it illustrates the multiplier effect which results from investment in digital infrastructure.

4.6.3 INTERDEPENDENCE WITH OTHER INFRASTRUCTURE SECTORS

Since the 1990s, ICT has been integrated with practically all infrastructure activities, changing the way in which assets are operated, infrastructure services are delivered and how infrastructure services are demanded. For decades, the largest degree of interdependency in the national infrastructure system resulted from the demand for energy from the transport, waste, water and communications sectors. But as ICT is used in more and more activities it equally has risen to underpin the functionality of other infrastructure sectors.

ICT forms the basis for a transformation in the energy system, as it becomes integrated through the supply chain all the way to the final consumer. This includes its use in embedding distributed renewable energy generation sources into the grid and balancing international energy flows in transmission from reserved power sources (Wissner, 2011). It is also becoming more central to the actual distribution of energy on the demand side, via price and incentive based mechanisms, and improving the amount of information available to both operators and consumers (Ibid.). Advances in ICT are important aspects of the infrastructure strategies in each of the sectors considered in this report, in particular in relation to energy and transport.

4.6.4 KEY IMPACTS

Energy and Emissions: Rapid innovation in the ICT sector makes it extremely difficult to explore potential energy demand and emissions pathways over the long term. Indeed, the 'big data' revolution places data centres and other ICT storage facilities in the limelight as they can be extremely intensive users of energy and responsible for considerable emissions. To date however, energy and emissions considerations have played a very limited role in the planning, management and regulation of communications infrastructure across Europe, even as we move towards the delivery of Next Generation Networks (NGNs) (Coomonte *et al*., 2013).

Telecommunications operators are some of the largest emitters in the ICT sector and in the UK overall. For example, in 2007 BT consumed 0.7% of the UK's total electricity usage (over 2100 GWh) (BT, 2013). The predicted future growth in the number of connected devices and bandwidth demanded is highly likely to put pressure on this figure. The economic cost of this energy usage is the key driving factor for emissions reduction in the ICT sector.

Research on energy-aware backbone networks has demonstrated that by turning off spare devices whose capacity is not required to transport off-peak traffic, it is possible to easily achieve more than a 23% energy saving per year (Chiaraviglio *et al*., 2009). Moreover, an 8-22% reduction in energy demand from cellular network infrastructure could be achieved if network operators switched off redundant base stations during periods of low traffic (e.g. night time) (Oh *et al*., 2011).

It has been estimated that the availability and increased penetration of super-fast broadband infrastructure by 2024 could save 2.3 billion kms in annual commuting, 5.3 billion kms in annual business travel and 1billion kWh of electricity usage. This would come from firms utilising the benefits of telecommuting, video conferencing and by shifting part of their server capacity to (more energy efficient) public cloud platforms. After accounting for rebound effects (e.g. in increased residential energy demand), faster broadband infrastructure has the potential to save 1.6 million tonnes of carbon dioxide per annum (SQW, 2013). However, it should also be noted that in the past ICT improvements have not led to the reductions in travel demand which had been expected, and the DfT's Draft National Policy Statement for National Networks suggests that they are not expected to have a significant impact on travel demand (DfT, 2013).

Mobility and Lifestyle: The social impact of ICT is more and more evident as Internet connectivity becomes an essential requirement for everyday life (Zhao, 2008). Indeed, the greater flexibility over working and living patterns, provided by ICT connectivity, is changing how we routinely move around our environment (Sayah, 2013). These new patterns appear to have many advantages, although the evidence is not always clear cut (Wilks & Billsbury, 2007). The potential benefits of these changes can range from new and more efficient forms of business organisation, through to improved work-life balance for workers. Changes in mobility also create the potential for reducing peak traffic demand during rush hour periods, which could reduce the negative environmental impacts associated with capacity-stricken transportation systems (White *et al*., 2010). However, the expected demand for infrastructure services can be changed considerably by these shifting work and lifestyle patterns. Consequently, this requires greater consideration for how ICT systems should be adapted to support shifting economic and social activities (Helbing, 2013).

Cross-sector analysis

The NISMOD system model has been used to analyse the demands that infrastructure sectors make upon one-another. Energy-transport and water-energy interactions stand out as key interdependencies that will influence the future performance of each sector.

5.1 ENERGY-TRANSPORT INTERDEPENDENCIES

A key interdependency lies between transport and its future energy needs, particularly if a substantial increase in electricity generation is needed to power electric vehicles and for increased electrification of the rail network. While the majority of electric vehicle recharging is likely to take place at home, it also seems likely that substantial battery recharging infrastructure will be needed in the field (e.g. at garages, supermarkets, workplaces, etc.). Moreover, electrification of the transport sector would require large investment in additional generating capacity, national transmission networks and local distribution networks. To explore the implications those issues the energy and transport models have harmonised inputs through the Electrification of Heat and Transport (EHT) strategy. This strategy highlights important interdependencies between the energy (including space heating) and transport sectors, in order to meet UK energy and climate policy objectives.

5.1.1 KEY RESULTS

Figure 38 shows potential pathways for high penetrations of both plug-in hybrid electric vehicles (PHEV) and full electric battery (BEV) powered vehicles. We have assumed that the switch to electric vehicles will have no direct impact on the volume of car travel undertaken (other than via differential cost signals). In reality the differing characteristics of electric and conventionally-fuelled vehicles (particularly with regard to range) may lead people to alter their travel patterns, but the nature of this change will depend on the future path of technological development. While the switch to electric vehicles will have a significant impact on emissions this will depend on the future fuel mix for electricity generation.

Figure 39A show the resulting total impact on electricity consumption with high penetrations of BEVs and PHEVs by 2050; and Figure 39B shows the significant increase in electricity peak demand over the same period.

Figure 38: Aggregate annual vehicle Km disaggregated by vehicle fuel in 2050.

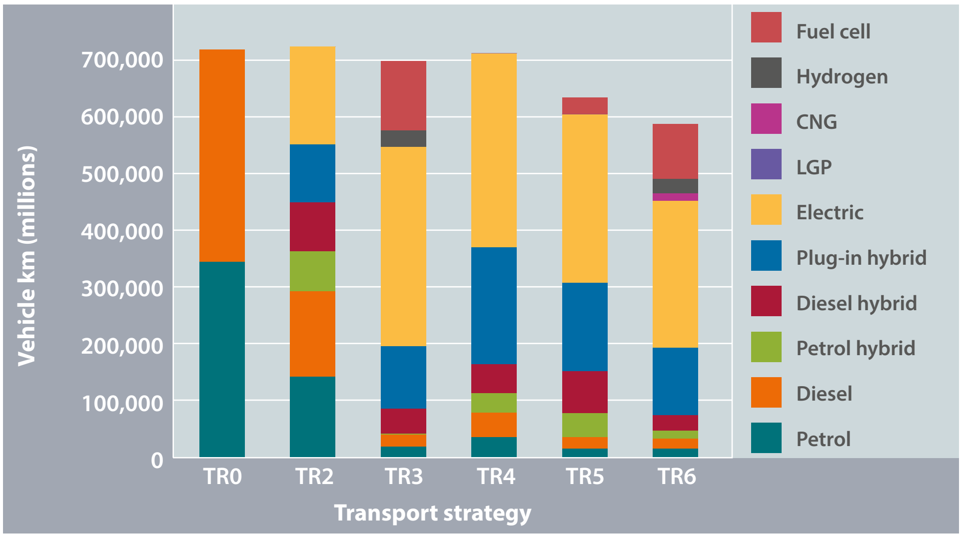


Figure 39: A) Total electricity consumption with high penetrations of BEVs and PHEVs in 2050. B) Change in electricity peak load with high penetrations of BEVs and PHEVs in 2050. Note: MPI, LEB and EHT energy strategies use TR0, TR2 and TR4 transport strategy outputs respectively. Only cars are assumed to charge from (G2V) and discharge to the grid (V2G demand response) during peak hours.

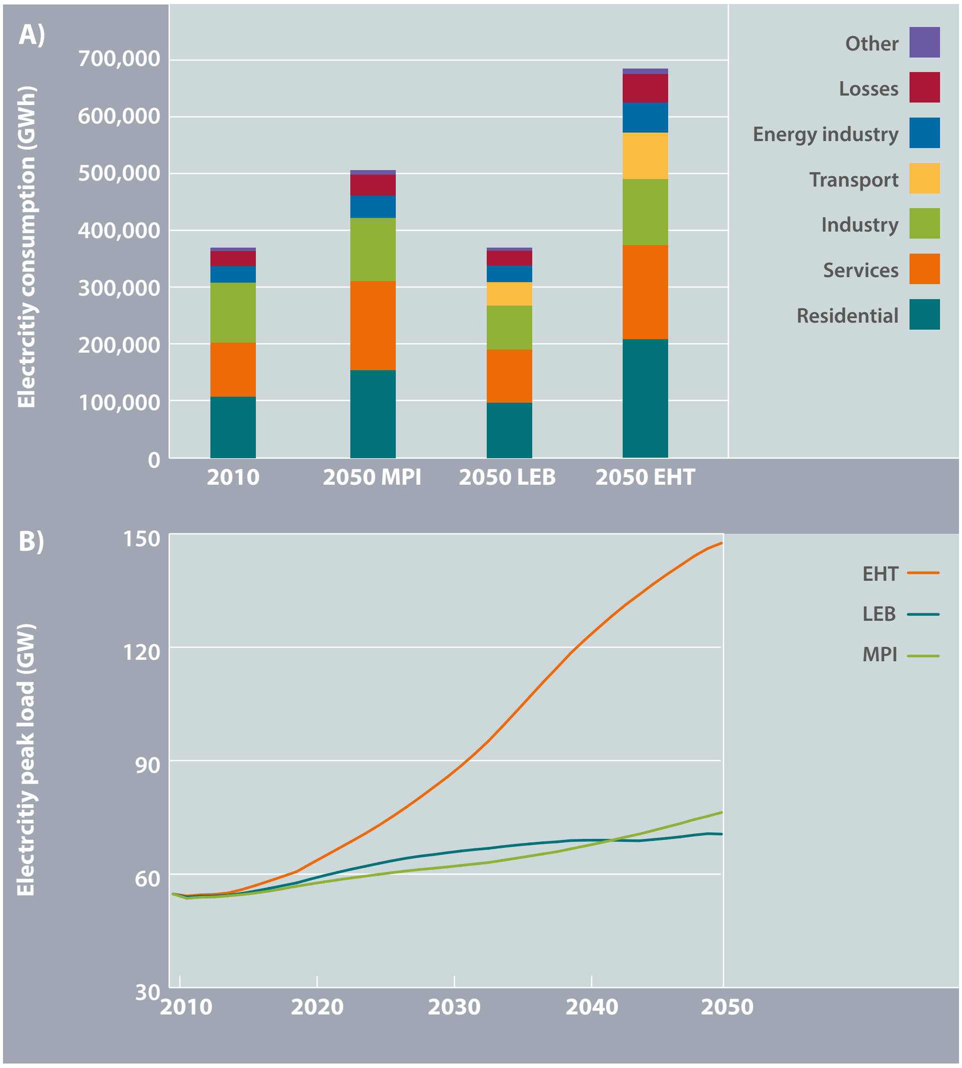


Figure 40 A – D shows the electricity demand for each modelled strategy indicating that decarbonising the transport sector along with electrifying domestic energy use via heat pumps requires sufficient low carbon electricity over the long-term. This depends upon investment into additional electricity generating capacity, with important differences in generation mix depending on which energy supply strategy is taken.

Figure 40: Electricity production by source per strategy A) MPI no carbon cost (MPI-noCC), B) MPI with carbon cost (MPI-CC) C) High Nuclear, D) High CCS, E) High Offshore.

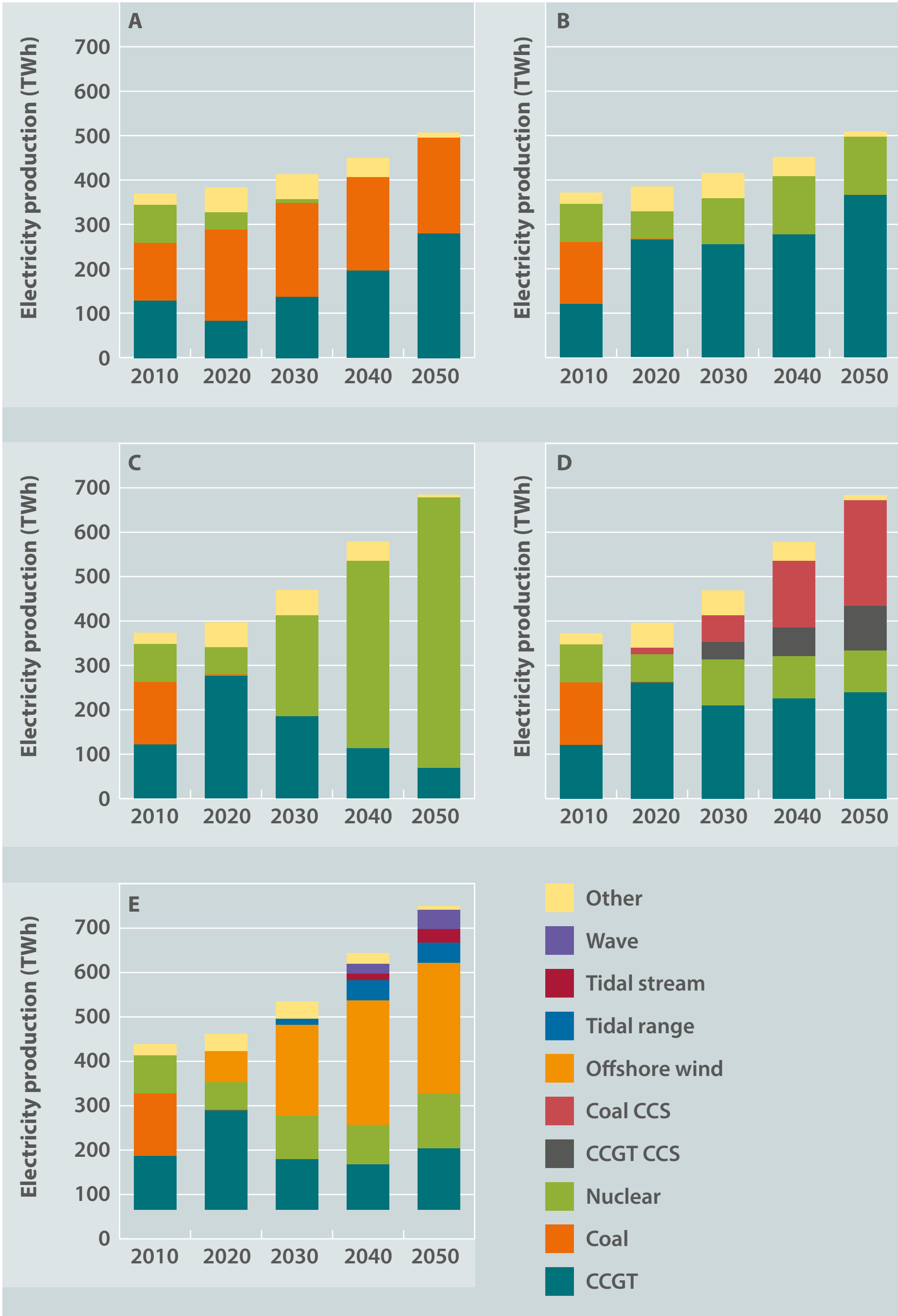
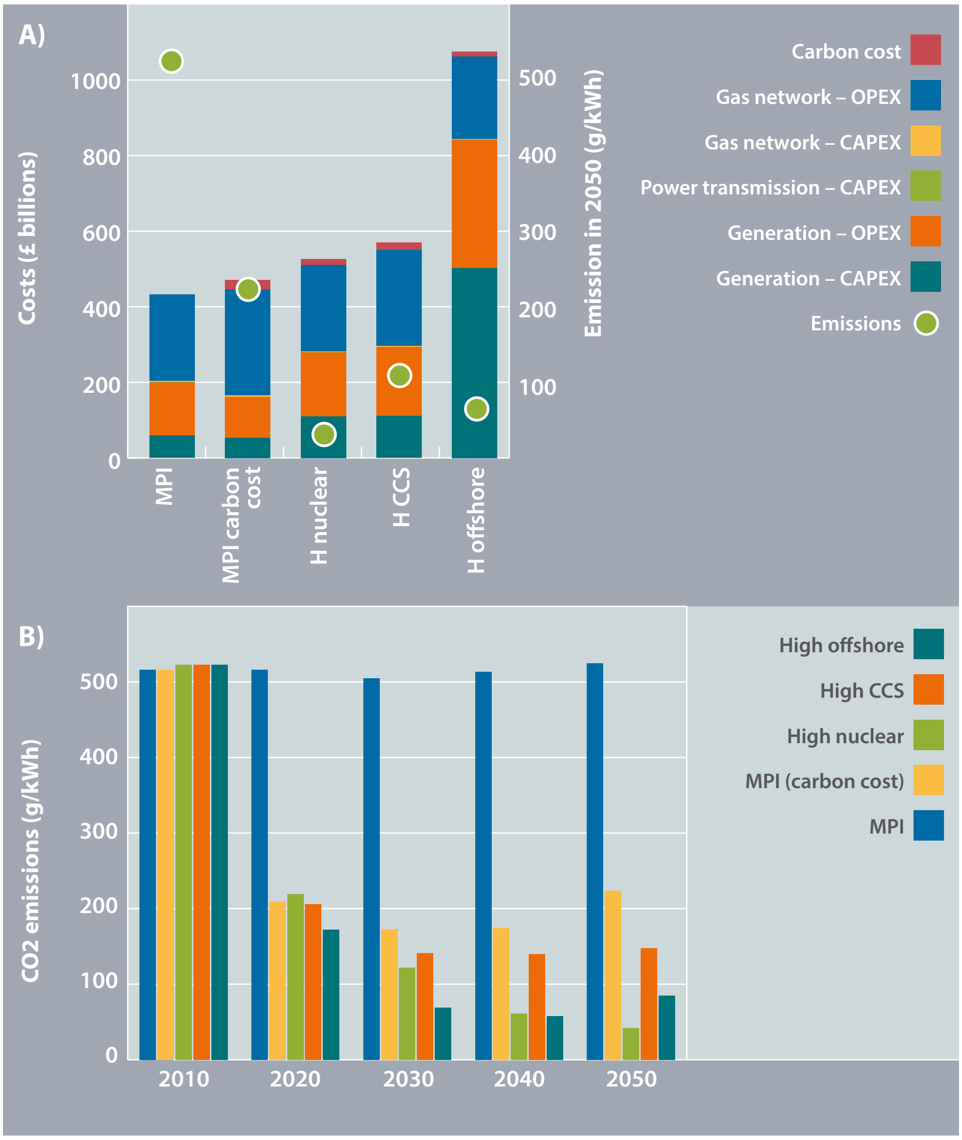


Figure 41 A and B provides cumulative investment in 2050 and change in carbon intensity for each strategy 2010 – 2050 respectively. This indicates the potential trade-offs between strategies in terms of necessary investment to achieve low carbon grid intensity. It is estimated that the grid carbon intensity has to drop to around 100 g/kWh from a current 500 g/kWh to gain the carbon reduction benefits of large scale deployment of electric vehicles (Tran *et al*., 2012).

Figure 41: A) Cumulative investment in 2050 and B) change in carbon intensity for each strategy 2010–2050.



5.1.2 KEY MESSAGES

Power generation investment costs indicates that decarbonising electricity generation with offshore renewables will come at the highest investment costs over the period 2010 – 2050 (~£1 trillion); whereas decarbonisation would be far less costly through increased nuclear (£500 billion) or CCS (£600 billion). However, part of the rationale for increasing the uptake of BEVs and PHEVs is for balancing the grid due to high penetrations of intermittent renewables. This however requires a strategic commitment to investment in renewables, which may have long-term benefits over the as yet unproven CCS and unresolved concerns over safety for nuclear.

5.2 WATER-ENERGY INTERDEPENDENCIES

The energy supply strategy taken to increase the amount of generation capacity for additional demand from transport, housing and future population growth also has important interdependencies with water availability. In the UK, the majority of thermal power plants use water for cooling, in addition to the existing hydro and pumped storage capacity. Currently the electricity sector is responsible for approximately 40% of 'non-tidal surface water' abstractions in England and Wales, as reported through Defra by the Environment Agency (2012). This figure, until recently, has been obscured by the inclusion of abstractions from hydropower.

Hydrological variability poses a risk to electricity generation that is dependent on water, thus power plants (both hydro and thermo-electric) are usually situated on bodies of water with reliable yields. Increasing demands from population growth and other industries may contribute to water scarcity that will be exacerbated by climate change. Due to the consumptive nature of thermo-electric generation, it is in the water regulator's interest to limit the levels of generation capacity that is developed in a river basin or catchment, in order to prevent over abstraction and maintain a reliable resource of water for an appropriate number of users. Over abstraction may lead to shortages not only for the energy sector but also to other sectors, and may also result in environmental damage and breach of environmental regulations, such as the Water Framework Directive (Environment Agency & Ofwat, 2011).

5.2.1 KEY RESULTS

Demands for water abstraction and consumption were calculated using the factors listed in Macknick *et al*. (2012a) and following similar methods to those used in Macknick *et al*. (2012b) and Byers *et al*. (2014). For each region, trajectories of future electricity generation are multiplied by abstraction and consumption water use factors and split by distributions that allocate generation to freshwater, tidal waters or sea water. Figure 42 show unconstrained demands for freshwater for each energy supply strategy. And Figure 43 shows regional disaggregation of water abstraction and consumption for each region for each energy strategy.

Figure 42: A) Freshwater abstraction, B) freshwater consumption per energy supply strategy 2010–2050. Note: High CCS (CCS); High Nuclear (Nuclear); High Offshore (Offshore); MPI no carbon cost (MPI no CC); MPI with carbon cost (MPI CC).

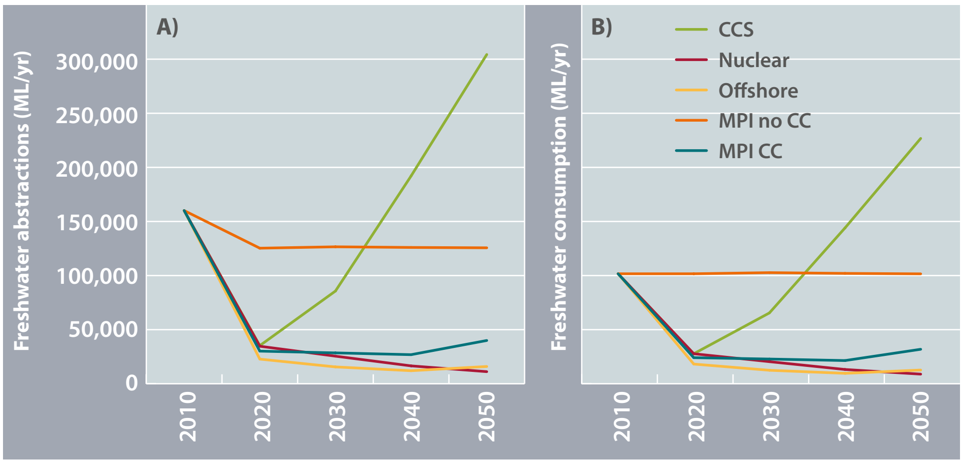
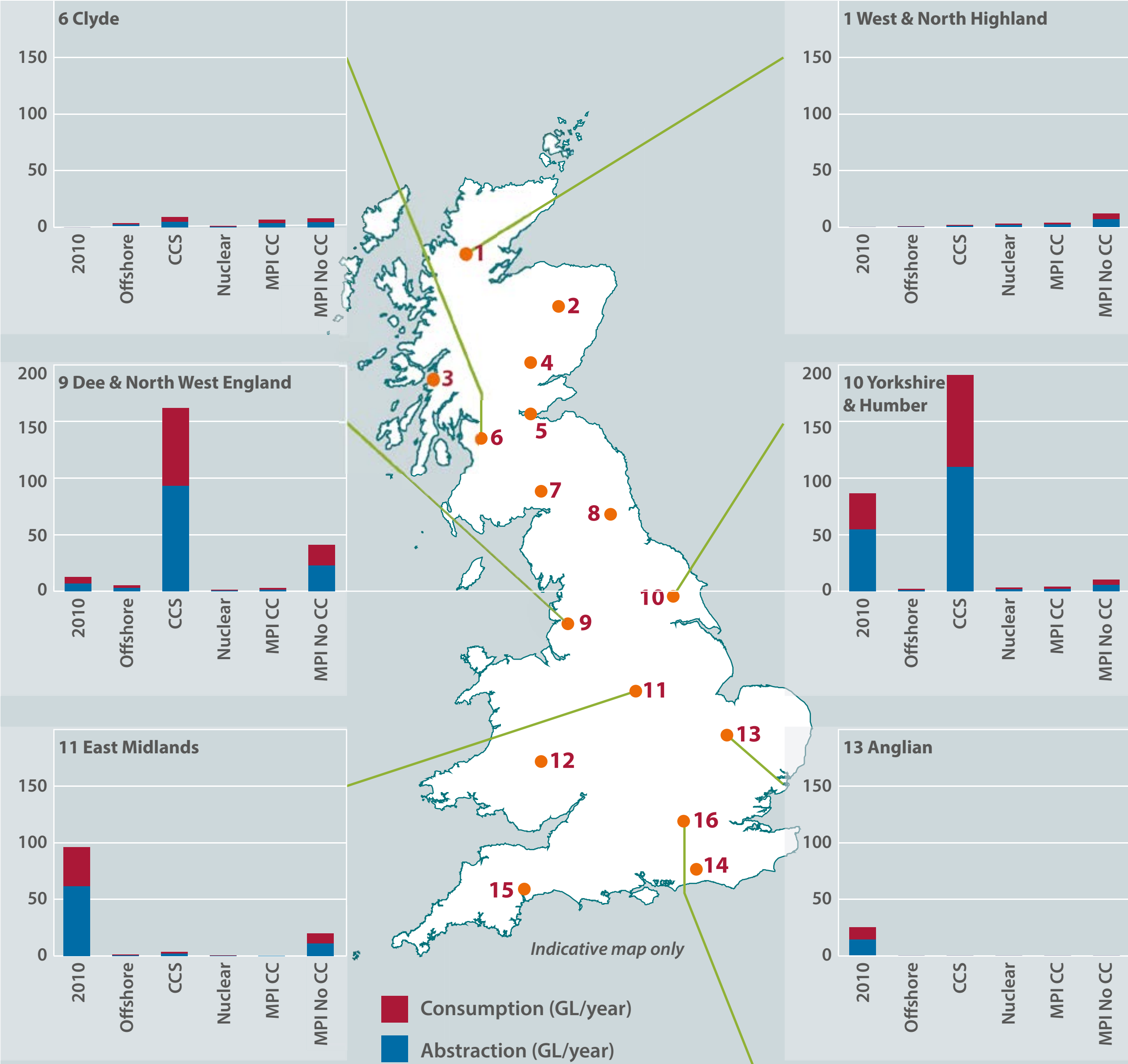


Figure 43 (overleaf): Water abstraction and consumption in 2010 and 2050 for each energy strategy disaggregated by region (GL/year). Note: High Offshore (Offshore); High CCS (CCS); High Nuclear (Nuclear); MPI with carbon cost (MPI CC); MPI no carbon cost (MPI no CC).



Abstraction (ML/year)	2010	Offshore	CCS	Nuclear	MPI CC	MPI-No CC
1 W&N Highland	0	280	851	1,314	1,699	5,521
6 Clyde	0	1,765	4,324	644	3,212	3,816
9 Dee & NW England	6,964	2,882	93,082	721	1,486	22,564
10 Yorkshire & Humber	54,659	1,002	109,824	1,836	2,277	5,649
11 East Midlands	61,278	704	2,014	378	158	10,939
13 Anglian	14,139	0	0	0	0	0
16 Thames	13,088	4,439	56,291	731	14,010	21,100
Others	9,951	4,893	37,914	5,572	17,152	56,068
Total	160,079	15,964	304,301	11,195	39,994	125,656
Abstraction (ML/year)	**2010**	**Offshore**	**CCS**	**Nuclear**	**MPI CC**	**MPI-No CC**
1 W&N Highland	0	169	603	1,023	1,284	4,357
6 Clyde	0	1,362	3,380	486	2,500	2,960
9 Dee & NW England	5,598	2,316	68,844	579	1,195	18,349
10 Yorkshire & Humber	31,743	805	81,340	1,476	1,830	4,596
11 East Midlands	34,364	566	1,619	304	127	8,919
13 Anglian	11,503	0	0	0	0	0
16 Thames	10,679	3,568	42,400	587	11,261	17,176
Others	8,119	3,933	29,336	4,479	13,787	45,577
Total	102,007	12,719	227,523	8,934	31,985	101,934

In the MPI without carbon cost, both abstraction and consumption of freshwater remains fairly stable through to 2050 due to little change in the generation mix. The other four strategies have a sharp reduction in abstractions and consumption towards 2020 due to closure of all coal-fired capacity. The high water intensity of CCS equipped generation results in gradually increasing abstraction and consumption. Despite having dropped to a quarter of current levels by the 2020s, water use surpasses current levels at around 2035 and is twice the current level in 2050. With the anticipation that there could be limited freshwater supplies in the future, for coal power to have a future in the generation mix of the UK, its generation will need to be, not only low-carbon through the use of CCS, but also sited on tidal or coastal sites where water for cooling is not scarce. The high water intensity of coal power with CCS (approximately double and quadruple that of unabated coal and gas power, respectively), in combination with the UK Government's CCS Roadmap strategy (DECC, 2012a) that encourages clustering of CCS infrastructure, is likely to increase localised water demands in industrial areas (Byers *et al*., 2014).

Cooling water abstractions for tidal sites are dominated by the use of once through cooling at a large number of sites, particularly for CCS and nuclear generation. Hence, the strategies for CCS and Nuclear have increasing levels of tidal water abstraction, with 2050 levels approximately 55% higher than 2010. In both of the strategies for MPI, tidal water use remains at similar volumes, whilst for the High Offshore strategy water abstraction and consumption decrease by 2050 to approximately 15% of the 2010 volumes.

Sea water abstractions, in most cases, are expected to increase, due to a variety of reasons, such as freshwater constraints and capital and operational cost efficiencies. There is a seven-fold increase in abstraction of sea water for cooling in the nuclear strategy, compared to changes of −35% to +119% witnessed in the other four strategies.

For the policies MPI without carbon cost (MPI noCC) and high CCS the continued presence of coal power in the generation mix leads to considerable increases in freshwater abstraction and consumption for busbars 9, 10 and 16 – equivalent to the river basin regions of Dee & NW England, Yorkshire and the Humber, and the Thames region. For the MPI with a carbon cost (MPI-CC), nuclear and offshore strategies, freshwater abstraction and consumption is reduced significantly in all the regions, besides the demand for development in MPI-CC in the Thames region which sees a reduction followed by an increase approaching 2050.

Our assessment of regional water resources considered what flows were available in the largest rivers at a Q95 level. A Q95 is the 5th percentile flow and indicator of extreme low flows; measured from the flow duration curve it represents the flow level exceeded 95% of the time for the duration of the historical flow record. We have assumed that licensed abstractions for the sector do not greatly exceed volumes that are currently abstracted. Furthermore, levels of capacity permitted on freshwater were limited to a maximum of 0-40% of the whole capacity for that period, depending on the capacity type, whilst the rest was allocated to tidal and sea water. The penetration of hybrid cooling on freshwater in 2050 was 30% for coal and gas-based technologies, with an additional 10% of air-cooled capacity. The assessment was made with respect to historical Q95 flow levels, which are probably higher than those that will be experienced with the expected impacts climate change.

Considered on an instantaneous basis (in m3/s) for each strategy, none of the regions have levels of generation capacity allocated to freshwater whose abstractions are expected to exceed the current Q95 levels, based on the assumed load factors, water source distributions and cooling technologies. If the allocation to different water sources was not determined, it could be expected that for regions 8-16, particularly for the CCS and MPI NoCC strategies, abstractions may exceed the available resource if Q95 low flows occur. This could be mitigated with even higher penetrations of hybrid cooling, higher allocations to tidal and sea water sources, or higher licensed volumes (unlikely).

5.2.2 KEY MESSAGES

- Freshwater abstractions and consumption can be expected to decrease, primarily due to the closure of current coal capacity.
- If the UK 'does nothing', or if the adoption of CCS equipped generation capacity is aggressively pursued freshwater abstractions and consumption, will be the same, if not significantly increase.
- The Large Combustion Plant Directive and decommissioning of current coal and nuclear capacity puts the UK on a sustainable, low-water trajectory for electricity generation.
- The High Offshore strategy is the best alternative for minimising all types of water use and impacts on aquatic environments.
- Strategies which minimise freshwater consumption but have higher levels of tidal and sea water use (i.e. MPI CC and High Nuclear) may also be good alternatives, if they can operate within acceptable local environmental constraints.
- The analysis assumed regional limits of capacity development on freshwater sources, in tandem with increased penetration of hybrid cooling. Without these constraints it is expected that demands for freshwater could possibly exceed available resources at low flows, regardless of the expected impacts of climate change and population growth on hydrological resources.
- Only the most water efficient generation capacity should be permitted to use freshwater for cooling, whilst more water intensive technologies should be limited to using tidal and sea water.

5.3 FUTURE INFRASTRUCTURE PATHWAYS FOR THE UK

Future strategic pathways are based on the assessment of Policy Portfolios, which are comprised of sector level strategies and used to contrast and compare the total system performance of national infrastructure. Important spatial and temporal trade-offs and synergies are identified in terms of return on investment, environmental performance, capacity expansion and demand reduction. The assessment of Policy Portfolios includes:

- *Minimum Intervention (P-MI)* – reflects historical levels of investment, continued maintenance and incremental change in the performance of the current system.
- *Long-term Capacity Expansion (P-CE)* – focuses on large scale, long-term investment into physical capacity expansion to meet increasing demand.
- *Increasing System Efficiency (P-SE)* – focuses on deploying the full range of technological and policy interventions to increase efficiency of the current system targeting both supply and demand.
- *New Services and Planning (P-NS)* – focuses on restructuring the current mode of infrastructure service provision through long-term investment in innovation and design of new service delivery models. A combination of targeted centralisation and decentralisation approaches are deployed.

The current portfolio analysis is based on a sample of sector level strategies (with the exception of transport) and should only be considered interim results. The full sectoral strategies that comprise each portfolio will be presented in the forthcoming Cycle 2 assessment in spring 2014.

5.3.1 MINIMUM INTERVENTION (P-MI)

This portfolio of strategies takes a general approach of minimum intervention beyond ensuring the on-going maintenance and operation of currently available infrastructure. Investment follows current trends with no major future investment to expand or modify the existing system. There is no long-term vision to reduce future demand or commitment to environmental policy. This portfolio focuses on short-term incremental improvements at the sector level, and does not account for increasing sectoral interdependencies. Advanced technologies such as ICT, new policies (incentives and penalties), and integrated planning and design are not leveraged to alter conventional capacity provision, or influence end-use demand. Table 5 summarises the sampled strategies in this portfolio.

Table 5: Sampled strategies to test Minimum Intervention Portfolio.

Minimum Intervention Portfolio [P-MI]				
Energy	**Transport**	**Water Supply**	**Wastewater**	**Solid Waste**
ENO – Minimal Policy Intervention	TRO – Decline and Decay	WRO – Current Trends (Central population scenario)	WWO – Current Trends (Central population scenario)	WEO – Current Trends

Figure 44 shows cross sector performance based on cumulative investment and per annum carbon emissions. By 2050, cumulative investment reaches nearly £600 billion, which is dominated by increasing energy supply capacity to meet growing demand. Water supply and waste water comprises around 20% of total investment by 2050, with nearly no additional investment into the transport network and solid waste infrastructure. The main consequence of this low investment portfolio is a decline in quality services coupled with poor environmental performance. This is shown by a 40% increase in carbon emissions reaching 400 $MtCO_2$ in 2050 from 2010 levels. Without substantial additional investments across all sectors infrastructure will have negative implications for meeting stated UK energy and climate policy targets.

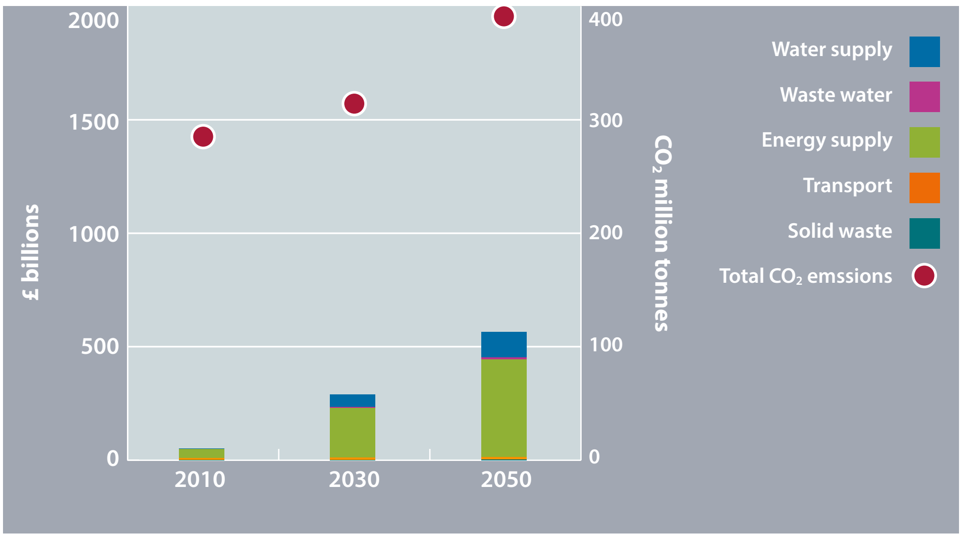


Figure 44: Minimum Intervention Portfolio performance based on cumulative investment and per annum carbon emissions. Note: Sampled strategies include energy (EN0), transport (TR0), water supply (WR0) and waste water (WW0) with central population growth scenario), and solid waste (WE0).

Impact Summary:

- This portfolio delivers incremental change to the overall system, and marginal impacts on long-term performance.
- Capacity provision increases incrementally with minor prioritisation of regional demand trends to meet short-term demand growth.
- Demand continues to rise with increasing capacity constraints across all regions in the medium to long-term.
- Investments increase following historical trends.
- Carbon emissions steadily rise due to incremental investment resulting in poor quality services and continued rising demand.

5.3.2 LONG-TERM CAPACITY EXPANSION (P-CE)

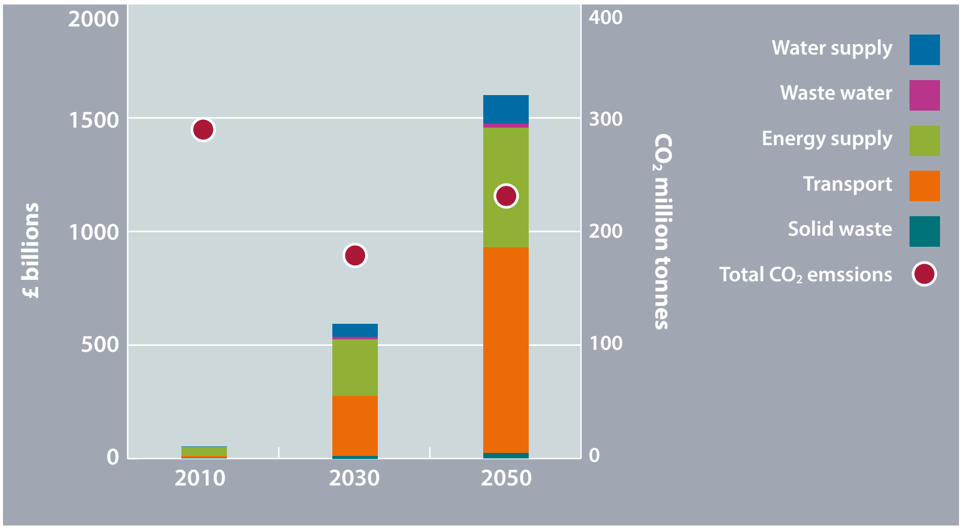
This portfolio of strategies focuses on planning for the long-term by increasing investment now to avoid capacity constraints in the future. Priority is given to the expansion of physical capacity to alleviate pinch-points and bottle-necks soon after they are identified. This portfolio may be less economically efficient at standard discount rates, and less robust to future uncertainties unless optionality can be in-built, but can save costs in the long run (close to "predict and provide" or the FTA "capacity intensive").

This portfolio is effective at meeting demand in the short to medium-term, but performs poorly over the long-term due to physical limitations in capacity expansion, lock-in to current technology and design, and no long-term vision to reduce or redistribute demand. There is also marginal commitment to environmental policy causing trade-offs between increasing capacity but poor environmental performance over the long-term. There is no reframing of the current mode of infrastructure service provision with continued investment into conventional technology and design, and little forward planning to address increasing sector level interdependencies. Table 6 summarises the sampled strategies in this portfolio.

Table 6: Sampled strategies to test Long-term Capacity Expansion Portfolio.				
Long-term Capacity Expansion Portfolio [P-CE]				
Energy	Transport	Water Supply	Wastewater	Solid Waste
EN2 – Electrification of Heat and Transport with High Nuclear	TR1 – Predict and Provide	WRO – Current Trends (High population scenario)	WWO – Current Trends (High population scenario)	WE1 – High Tech

Figure 45 shows cross sector performance based on cumulative investment and per annum carbon emissions. By 2050, total cumulative investment reaches £1.6 trillion with transport beginning to overtake energy supply by 2030 and dominating total investment by 2050. There are also relatively significant increases in investment for solid waste and water supply. Over the medium term this portfolio reduces carbon emissions from major investments into nuclear power generation, but over the long-term emissions increase from the massive expansion of transport infrastructure and rising demand. Consequently, carbon emissions nearly reach 250 $MtCO_2$ in 2050, almost equal to 2010 levels, despite high investment into nuclear power generation. Consequently, emission reductions made in the energy sector are lost due to increasing transport capacity expansion. This demonstrates the importance of a harmonised investment approach that accounts for cross sector performance and interdependency.

Figure 45: Long-term Capacity Expansion Portfolio performance based on cumulative investment and per annum carbon emissions. Note: Sampled strategies include energy (EN2 with High Nuclear), transport (TR1), water supply (WR0) and waste water (WW0) with high population growth scenario), and solid waste (WE1).



Impact Summary

- This portfolio delivers large-scale change to the current system, with improved performance over the short to medium-term, but is less robust over the long-term due to physical capacity limitations, increasing demand, and lock-in to conventional technology and design.
- Capacity rapidly increases over the short to medium-term across most regions, but reach physical limitations in the most densely populated areas over the long-term.
- Demand is met in the short to medium-term, but over the long-term there are increasing bottlenecks due to physical limits in capacity expansion.
- Investment increases dramatically over the entire period.
- Carbon emissions reductions may be achieved in the medium term from improved infrastructure performance, but rise over the long-term due to increasing capacity expansion and demand growth.
- Without a coordinated investment approach that targets sectoral interdependencies, performance gains in one sector (energy) are lost in other sectors (transport).

5.3.3 INCREASING SYSTEM EFFICIENCY (P-SE)

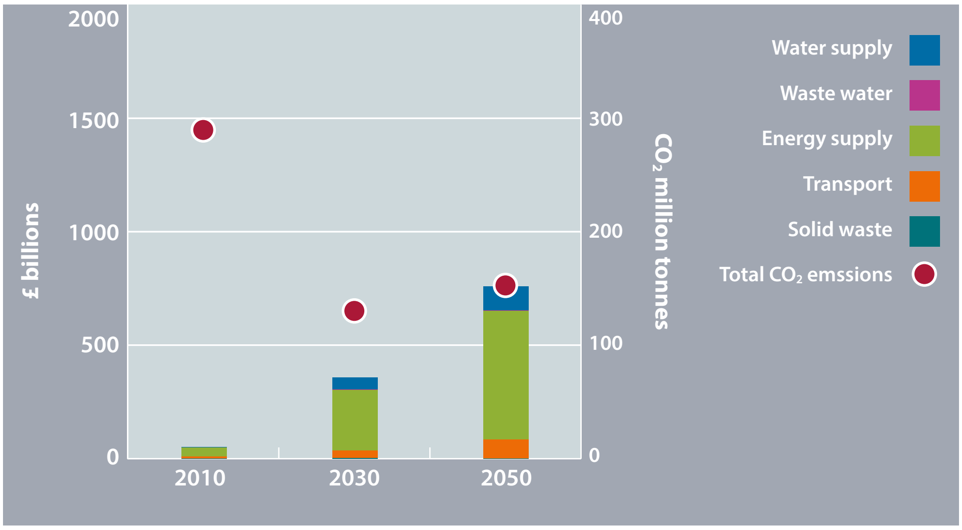
This portfolio of strategies focuses on optimising the performance of the current system. These strategies leverage the full range of new technological innovations (ICT), and policies (incentives/penalties) to increase supply-side operational efficiency, and influence end-use demand. There is targeted investment to increase capacity at severe bottlenecks in the short-term, but the medium to long-term vision is to invest heavily to maximise throughput of the current system, without massive investments into capacity expansion. There is an important strategic shift in reframing the provision of infrastructure services by identifying and prioritising economic trade-offs and synergies between supply and demand. This reframing is strongly influenced by environmental policy and industry innovation to reduce carbon emissions along the entire supply chain, and increasing forward planning to capitalise on sectoral interdependencies.

There are important trade-offs between this portfolio and physical capacity expansion (P-CE) which will likely perform better in the short to medium-term in alleviating bottlenecks. The Systems Efficiency (P-SE) portfolio may not be competitive until the medium-term if it can meet demand at less cost than physical expansion through steady operational efficiency improvements, and demand reduction. However, without a fundamental change in system design, performance of this portfolio over the long-term is less robust if efficiency improvements reach thermodynamic limits, or are ultimately outpaced by long term demand growth. Table 7 summarises the sampled strategies in this portfolio.

Table 7: Sampled strategies to test Increasing System Efficiency Portfolio.				
Increasing System Efficiency Portfolio [P – SE]				
Energy	Transport	Water Supply	Wastewater	Solid Waste
EN2 – Electrification of Heat and Transport with High CCS.	TR3 – Adapting the Fleet	WR0 – Current Trends (Low population scenario)	WW0 – Current Trends (Low population scenario)	WE3 – Deep Green

Figure 46 shows cross sector performance based on cumulative investment and total per annum carbon emissions. By 2050, total cumulative investment increases to nearly £800 billion with energy supply dominating investment throughout the modelled period. Investment into water and transport are nearly equal, at around 10% each of total investment by 2050. Over the medium term this portfolio performs well. By 2030, annual carbon emissions decline by 50% reaching 130 $MtCO_2$ through efficient transport networks, high investment into carbon capture and storage (CCS) for power generation, and levelling demand trends in the water sector. However, over the longer term, without a major restructuring of infrastructure service provision, efficiency gains are lost from rising demand trends shown by an increase in carbon emissions reaching 150 $MtCO_2$ in 2050.

Figure 46: Increasing System Efficiency Portfolio performance based on cumulative investment and per annum carbon emissions. Note: Sampled strategies include energy (EN2 with High CCS), transport (TR3), water supply (WR0) and waste water (WW0) with low population growth scenario, and solid waste (WE3).



Impact Summary

- This portfolio delivers moderate level change to the current system depending on where and when efficiency gains can be achieved at least-cost. The portfolio performs well over the medium-term but may be less robust over the long-term if continued demand growth outpaces efficiency improvements.
- Capacity provision increases over the short to medium-term but far less than the Capacity Expansion Portfolio (P-CE) over the long-term.

- Demand is met in the short to medium-term, but over the long-term there could be bottlenecks in the highest growth regions due to long-term demand trends surpassing efficiency improvements.
- Investments increase substantially over the short to medium-term but far less than Capacity Expansion (P-CE) and New Services and Planning (P-NS) over the long-term.
- Carbon emissions decrease in the medium term from efficient transport networks, high investments into CCS for power generation, and suppressed demand trends in water supply, but over the long term begin to rise.

5.3.4 NEW SERVICES AND PLANNING (P-NS)

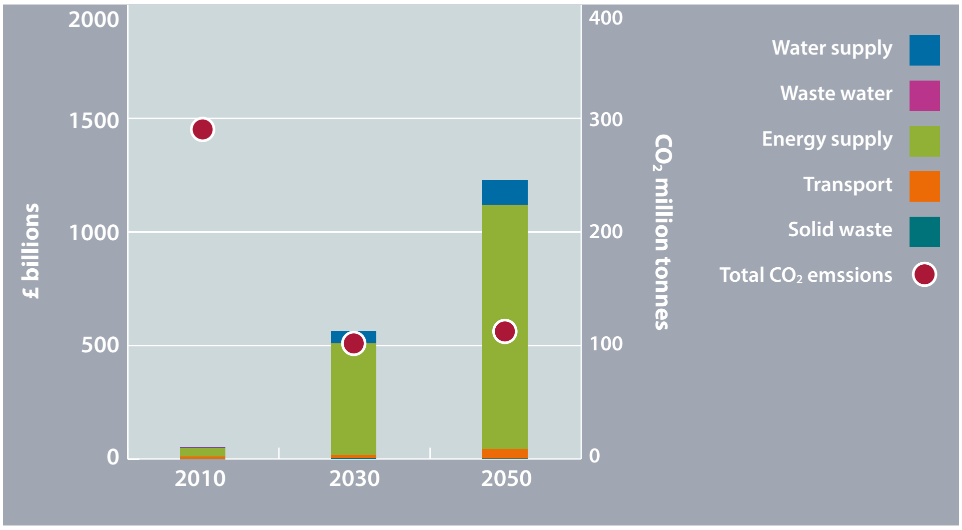
This portfolio of strategies focuses on fundamentally redesigning the current infrastructure system to improve total system performance. There is an important strategic shift in reframing the provision of infrastructure services from one of physical capacity expansion to the uninterrupted flow of goods and services. This results in identifying trade-offs and synergies along the entire service delivery chain and capitalising on sectoral interdependencies. This portfolio leverages the full range of technological innovation, policy incentives, and integrated planning and design through maximum use of ICT for operational planning and behaviour change. There is a strong commitment to environmental policy coupled with long-term investment to incentivise new service delivery models. The general approach is to deploy the right balance of centralised and decentralised strategies depending on regional and temporal trade-offs, such as determining where and when benefits from economies of scale can be achieved versus reducing long-term demand, or increasing capacity in the short-term versus reducing carbon emissions over the long-term.

There are important trade-offs between this portfolio (P-NS) and Long-term Capacity Expansion (P-CE) and Increasing Systems Efficiency (P-SE). Capacity expansion will be competitive in the short-term and systems efficiency in the medium-term, with some exceptions in transport where capacity expansion can have long lead times compared to efficiency gains through targeted consumer behaviour. New Services and Planning could deliver regionally dispersed benefits in the short to medium-term through decentralisation. However, large-scale benefits may not be realised until the long-term when economies of scale can be achieved. But this will require sustained investment to restructure the current delivery system, large-scale diffusion of advanced supply-side technologies, and major shifts in demand away from current consumption patterns. However, this portfolio is the most robust against long-term trends in demand growth, where the other portfolios fall short. Table 8 summarises the sampled strategies in this portfolio.

Table 8: Sampled strategies to test New Services and Planning Portfolio.				
New Services and Planning [P – NS]				
Energy	Transport	Water Supply	Wastewater	Solid Waste
EN2 – Electrification of Heat and Transport with High Offshore	TR6 – Smarter Choices	WRO – Current Trends (Low population scenario)	WRO – Current Trends (Low population scenario)	WE3 – Deep Green

Figure 47 shows cross sector performance based on cumulative investment and per annum carbon emissions. By 2050, total cumulative investment reaches £1.2 trillion driven by high investments into renewables and offshore energy supply infrastructure. There are marginal investments into transport capacity expansion due to major changes in travel demand patterns over the long term. Demand trends in the water sector also levels off requiring proportionately lower capacity investment of less than 10% of the total in 2050. As a result, this portfolio achieves a 60% decline in annual carbon emissions reaching 100 $MtCO_2$ in 2030 and maintaining similar levels in 2050.

Figure 47: New Services and Planning Portfolio performance based on cumulative investment and per annum carbon emissions. Note: Sampled strategies include energy (EN2 with High Offshore), transport (TR6), water supply (WR0) and waste water (WW0) with low population growth scenario, and solid waste (WE3).



Impact Summary

- This portfolio delivers large-scale change to the current system over the long-term. It could perform unevenly in the short to medium-term depending on specific regional and local circumstances, but is likely to be the most robust across all regions over the long term due to major reductions in demand.
- Capacity provision increases over the short to medium-term but distributed unevenly across regions depending on where economies of scale can be achieved.
- Demand steadily increases in the short to medium-term resulting in bottlenecks in high growth regions, but reduces significantly over the long-term across most regions.
- Investments increase substantially over the entire period without pay back until the medium to long-term.
- Carbon emissions could dramatically decouple from economic growth over the long-term due to major structural redesign and sustained reductions in per capita demand.

5.3.5 COMPARATIVE PORTFOLIO ANALYSIS

Figure 48 shows the comparative performance between portfolios over time (2010 – 2050). There are important differences in cumulative investment between portfolios with a range of £560 billion to £1.6 trillion by 2050 for the Minimum Intervention and Capacity Expansion Portfolios respectively. Over the same time, cumulative investment for Increasing Systems Efficiency is £765 billion and New Services and Planning is the second highest reaching £1.2 trillion.

Investment is dominated by energy supply across all portfolios except for Capacity Expansion where massive investments are made in transport infrastructure, resulting in high levels of long-term carbon emissions. Conversely, Increasing Systems Efficiency has the potential to incur only half the investment cost as Long-term Capacity Expansion while achieving major carbon emissions reduction. Not surprisingly, to restructure the current infrastructure system over the long-term through New Services and Planning incurs substantial investment costs, second only to Capacity Expansion. However, this could also achieve major carbon emission reductions out performing Increasing Systems Efficiency by 2050.

There are also important differences in future environmental performance between portfolios. In 2050 the best performing portfolio is New Services and Planning with emissions of 110 $MtCO_2$ compared to a high of 400 $MtCO_2$ for the Minimum Intervention Portfolio. Importantly, all portfolios achieve carbon emission reductions in 2030 except for the Minimum Intervention Portfolio with a continued increase in carbon emissions over the long term. Additionally, while performance gains are made over the medium term, by 2050 only Increasing Systems Efficiency and New Services and Planning appear to be robust against long-term rising population growth trends.

Although these results are based on a sample of model runs, we do not expect the general comparative performance to change significantly. With the complete set of Portfolios we expect to have higher resolution spatial and temporal results to compare portfolio performance further indicating important trade-offs and synergies. Even with the sampled results to demonstrate the Portfolio performance, we can see that a key message is that all sectors need to invest heavily to improve total system performance in terms of continued service provision and carbon emissions reduction to meet economic and environmental policy goals.

Figure 48: Comparative analysis of portfolio performance based on cumulative investment and per annum carbon emissions (2010–2050).

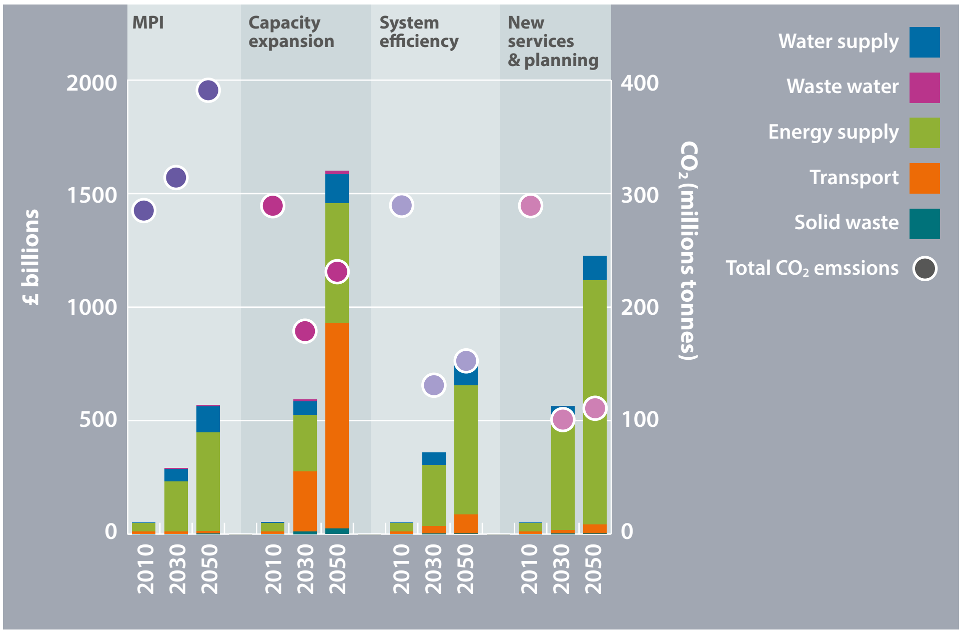
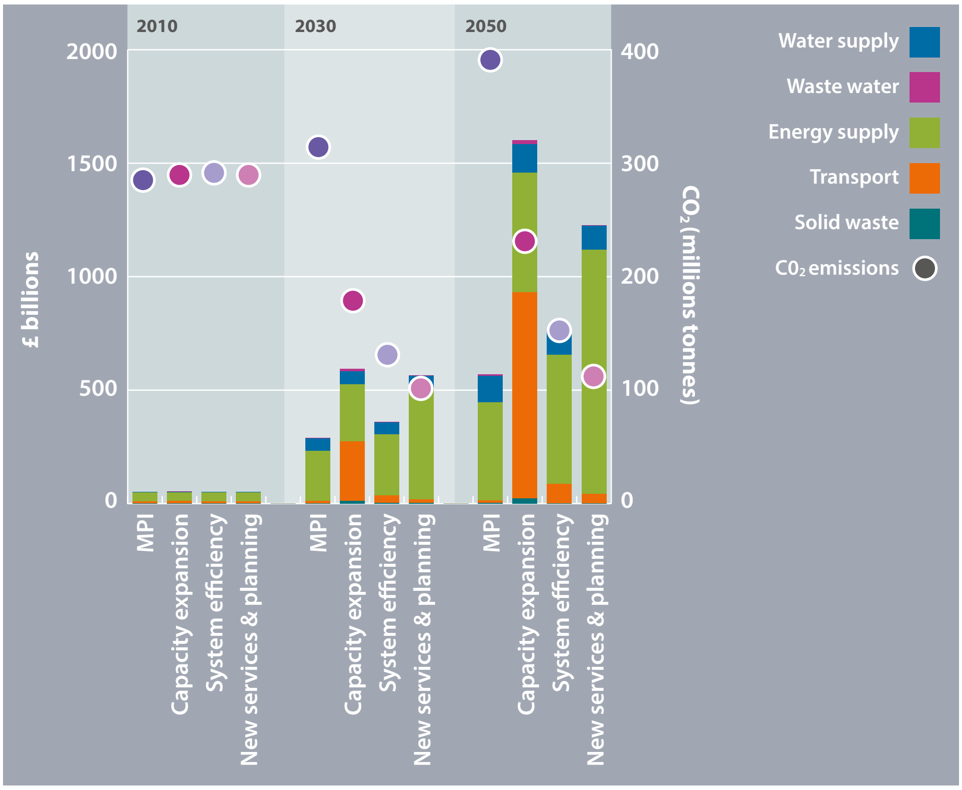


Figure 49 compares the performance of each portfolio at different time steps. We can see that in the medium term (2030) investment between Capacity Expansion and New Services are both around £600 billion but with major differences in sector level investment with the former dominated by transport and the latter by energy supply. There are also important differences between the two in environmental performance with Capacity Expansion nearly double the carbon emissions of New Services. However, by 2050, both cumulative investment and carbon emissions for Capacity Expansion far exceed all other Portfolios except for the high carbon emissions from the Minimum Investment Portfolio.

In 2030, investment in Increasing Systems Efficiency and Minimum Intervention are similar approaching £400 billion. However, with relatively smaller increases in investment compared to other portfolios, Increasing Systems Efficiency is able to achieve far greater carbon emissions reduction by 2050. We expect that the full ensemble of strategy runs will reveal more insight into the potential comparative advantages between portfolios at different time steps.

Figure 49: Performance comparison of each portfolio based on cumulative investment and per annum carbon emissions for 2010, 2030, 2050.



5.3.6 KEY MESSAGES

- The Minimum Intervention Portfolio (P-MI) delivers incremental change to the overall system, and marginal impacts on long-term performance.
- The Long-term Capacity Expansion Portfolio (P-CE) delivers large-scale change to the current system, with improved performance over the short to medium-term, but is less robust over the long-term due to physical capacity limitations, increasing demand, and lock-in to conventional technology and design.
- The Increasing Systems Efficiency Portfolio (P-SE) delivers moderate level change to the current system depending on where and when efficiency gains can be achieved at least-cost. The portfolio performs well over the medium-term but may be less robust over the long-term if continued future demand growth outpaces efficiency improvements.
- The New Services and Planning Portfolio (P-NS) delivers large-scale change to the current system over the long-term. This portfolio may perform unevenly in the short to medium-term depending on specific regional and local circumstances, but is possibly the most robust across all regions over the long term due to major reductions in long-term demand trends, but also faces a high degree of investment uncertainty.

- There are important differences in cumulative investment between portfolios with a range of £560 billion to £1.6 trillion by 2050 for the Minimum Intervention and Capacity Expansion Portfolio's respectively. Over the same time, cumulative investment for Increasing Systems Efficiency is £765 billion and New Services and Planning is the second highest reaching £1.2 trillion. Investment is dominated by energy supply across all portfolios except for Capacity Expansion where massive investments are made in transport infrastructure, resulting in high levels of carbon emissions by 2050.
- There are important differences in future environmental performance between portfolios. In 2050 the best performing portfolio is New Services and Planning with emissions of 110 $MtCO_2$ compared to 400 $MtCO_2$ for the Minimum Intervention Portfolio. While performance gains are made over the medium term, by 2050 only Increasing Systems Efficiency and New Services and Planning appear to be robust against long-term rising population growth trends.

6 Delivering and governing our infrastructure system

The ITRC Fast Track Analysis (FTA) argued that the main governance challenges for UK infrastructures interdependencies include a complex governance landscape, created by the different arrangements of the 5 ITRC sectors, the existence of regulation at multiple geographical scales, and the need to implement policies to facilitate low-carbon transitions, innovation and to deal more systematically with interdependencies between sectors. Although the FTA report called for the state to play a significant role by implementing policy frameworks, regulations and incentives for investment and innovation, and to negotiate with a large number of other actors to effect change, it did not develop specific proposals for the governance of infrastructure interdependencies. Presented here are possible future frameworks for governing these interdependencies in the UK government, building on sectoral strategies that have been explored by the ITRC.

6.1 UK INFRASTRUCTURE GOVERNANCE CHALLENGES

During the 20th Century, the governance of most national infrastructure sectors has moved from a decentralised set of arrangements – with a mix of public and private provision – towards a national, market-led governance model. The evolution of institutions, rules, regulations, and ownership arrangements has been accompanied by an increasingly diverse set of actors. The most prominent governance actors are national government departments, economic regulators and environmental regulators. The European Commission has played an increasingly important role, especially in environmental regulation and in pushing for more open markets and competition. Governance at the local scale has also started to re-emerge – for example, through the Smart Cities agenda. Individual utility companies are also engaging at a local level with the governance of infrastructure interdependencies.

The National Infrastructure Plan (HM Treasury, 2013b) projects that significant investment in infrastructure will be required over the next few years, with over £375 billion of planned investment in the pipeline over the period to 2020 and beyond. Most of this investment (over £340 billion) is expected to be in the energy and transport sectors.

One way to help make this investment more efficient and effective would be to develop more opportunities for coordination within (and facilitated by) policy and regulatory frameworks. The Joint Regulators Group of sector economic regulators has recognised this, and has called for more "joint infrastructure investment" (JRG, 2013) within the UK.

6.2 GOVERNING FOR INFRASTRUCTURE INTERDEPENDENCY

The National Infrastructure Plan (HM Treasury, 2013b) highlighted the potential short and long-term impacts of physical ITRC infrastructure on UK economic growth and the importance of developing improved infrastructure networks. More strategic governance of infrastructure interdependencies (i.e. to encourage more effective use of infrastructure) is expected to increase these economic impacts. This could lead to: 1) unlocking more investment and economic growth; 2) delivering new capacity at lower costs; and 3) providing infrastructure maintenance at lower cost for the UK (Frontier Economics, 2012).

This co-ordination could be achieved partly through 'bundling' existing infrastructure systems with new infrastructure from different sectors (such as co-locating electricity and broadband; the transport network and utility infrastructure; and sewers and communications networks) and the development of infrastructure corridors.

The governance of infrastructure interdependencies should be considered not only in terms of security and vulnerability of critical infrastructure. The UK government and infrastructure providers have focused most of their attention on security and vulnerability so far, since this is where government has direct power to act. However, there is potential for economic and security gains to be made from the integration of this focus with a second dimension of governance: infrastructure coordination. This would involve the government and/or regulators acting as brokers of co-ordinated infrastructure development that involves a range of public and private actors across sectors.

Although the UK government may have a preference for voluntary arrangements for infrastructure co-ordination, there is a need for some more formal mechanisms to provide coherence and clarity. Existing informal and semi-formal governance arrangements like Utility Forums, which intermediate between a varied group of public and private actors should be complemented by a more formal co-ordination framework.

6.3 GOVERNANCE IMPLICATIONS OF THE ITRC ANALYSIS

The four policy portfolios that have been developed and applied in this report will require significantly different governance arrangements – including different approaches to the governance of interdependencies:

- The Minimum Intervention Portfolio emphasises the maintenance of current infrastructure systems, with little investment in new or expanded infrastructure systems and little attention to environmental sustainability. This implies a set of governance arrangements that are similar to those in place in many sectors in the immediate post-privatisation period in the UK. These were primarily concerned with short-term economic efficiency. This portfolio does not require governance arrangements to place a lot of emphasis on co-ordination between infrastructures.
- The Long-term Capacity Expansion Portfolio will involve a primary emphasis on supply side infrastructure investment and expansion to meet demand. Governance arrangements would need to provide clear incentives for this investment, and for infrastructure providers to take long-term decisions with comparatively low risks.

Like the first portfolio, there is little emphasis on environmental sustainability or on a more co-ordinated approach to infrastructure investment and operation.

- The Increasing System Efficiency Portfolio focuses primarily on making current infrastructure systems more efficient, and achieving higher levels of capacity utilisation. This will require fundamental governance and regulatory reforms so that infrastructure providers have a primary incentive to improve efficiency throughout infrastructure systems, to focus more on the demand side and to improve environmental sustainability. It will also require significant amounts of co-ordination within and between infrastructure sectors.
- The New Services and Planning Portfolio is the most radical portfolio. The governance implications are similar to those for the Increasing System Efficiency portfolio, but with much more emphasis on incentives for radical technical change, the widespread application of ICTs and for new business models. For this portfolio, a co-ordinated approach to governance across sectors will be essential, but this would not be implemented in an exclusively 'top down' way. The portfolio emphasises a 'mixed economy' for infrastructure governance in which local, regional, national and international governance all have roles to play. This will require effective co-ordination between these different governance levels.

Coordinated and significant energy and carbon reduction strategies in energy and transport will require new large-scale infrastructures and significant changes to existing infrastructures – especially if large-scale electrification of heat and transport takes place. However, if these strategies are to be implemented efficiently and effectively they will need to work across the 'policy silos' that sometimes exist between energy supply and demand, and between energy and transport.

Interactions between energy and water systems will increase under some future scenarios. This includes increasing use of water for cooling in power generation, a potential increase in the use of energy for water pumping and wastewater treatment, and (more speculatively) new demand for water associated with the potential development of onshore unconventional oil and gas. This will require similar increases in governance co-ordination between these sectors. As shown in the ITRC case study of water-electricity interactions, this co-ordination is also required to facilitate more investment in (and use of) sustainable, low carbon energy systems within the water sector.

6.4 GOVERNANCE RECOMMENDATIONS

- The UK government should adopt an integrated approach to governing infrastructure interdependencies. This would bring together the current primary focus on security and vulnerability concerns with more proactive incentives for coordination within and between infrastructure sectors.
- The UK government should specifically play a role in organising and facilitating platforms for establishing and developing infrastructure coordination between key stakeholders. This could be achieved by building on the experience of intermediary platforms like Local Resilience Forums and exploring synergies with governance arrangements already in place at the urban scale.
- The government and sector regulators should identify and tackle barriers to more infrastructure co-ordination. Our case study of water-electricity governance interactions shows that in some cases this co-ordination has been lacking and that there can be contradictory incentives for infrastructure providers from different sector regulators. The Joint Regulators Group has started to consider these issues. However,

if the issues identified in the ITRC water-electricity case study are reflected more widely, more specific regulatory and policy reforms will be required in conjunction with the relevant government departments and Infrastructure UK.

- Whilst there is a need for economic regulators to work together to minimise contradictory signals to infrastructure providers and to maximise synergies across sectors, they could also have a role in supporting the development of intermediary platforms for cooperation between key stakeholders. A good example is the Smart Grids Forum that is co-convened by Ofgem (the energy regulator) and the Department for Energy and Climate Change.

7 The road ahead for national infrastructure systems modelling

The need for a strategic approach for infrastructure provision in the UK is widely recognised. The 2013 National Infrastructure Plan set out the need for "a long-term sustainable plan, which means taking a cross-cutting and strategic approach to infrastructure planning, funding, financing and delivery taking an increasingly strategic approach." National Policy Statements are setting out the Government's objectives for the development of nationally significant infrastructure.

Sir John Armitt has argued for a National Infrastructure Commission which would "produce a National Infrastructure Assessment looking at the UK's needs over a 25–30 year time horizon… It will develop evidence about the state of the nation's assets and the likely impact of key economic, environmental and demographic trends… It would set out an overarching vision for the strategic development of our national infrastructure, taking account of the main interdependencies between the sectors."

In the analysis described in this report and the ongoing development of NISMOD, ITRC has not set out a single "overarching vision" but has analysed a series of alternative approaches to infrastructure provision in Britain and has then gone on, for the first time, to provide quantified assessment of the costs, performance and environmental sustainability of those alternatives. ITRC has assembled the evidence and developed the models of interdependent national infrastructure systems that would be required to support the work of the National Infrastructure Commission.

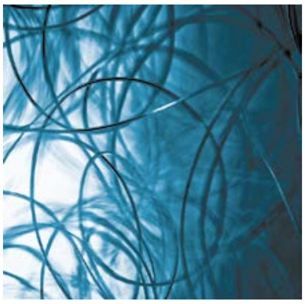
The results reported here form part of the ongoing ITRC research programme, supported by EPSRC. The results are currently being refined and a wider range of scenarios and strategies are being analysed. The final results from the ITRC's national infrastructure assessment will be reported in a book, to be published by Cambridge University Press in 2014: Planning Infrastructure for the 21st Century: Systems of systems methodology for analysing society's lifelines in an uncertain future. The manuscript of that book is now being finalised. We invite comments on the analysis presented in this report, which will help to ensure that the book is accurate and robust.

The ITRC's current phase of research will extend until the end of 2015. In the remaining two years of research we will:

- Undertake a new phase of model development to further integrate the sector models in NISMOD-LP that have been presented in this report. This will enable (i) more extensive sampling of scenarios and strategies and (ii) more dynamic representation of the interdependencies between sectors.

- Complete the development of the NISMOD-RV analysis of climate-related risks to infrastructure networks and the consequences of interdependence. This is already informing the identification of critical network vulnerabilities and will be used to target investment in infrastructure resilience.
- Complete the NISMOD-RD model of the relationship between infrastructure provision and regional development in Britain. This will include work (i) on the relationship between infrastructure provision and business location decisions and (ii) on the relationship between infrastructure and macro-economic growth.
- Further develop the functionality and content of the NISMOD-DB national infrastructure database, to enable scrutiny and visualisation of the datasets and NISMOD results.
- Deepen our work on the governance of infrastructure provision, with more specific recommendations on the governance of interdependent systems.

In undertaking this research we will continue to interact closely with our project partners in government, business and the engineering institutions. We will be further exploring the ways in which the ITRC analysis can be taken up in support of UK economic competitiveness and sustainable development. We will in particular be further deepening our links with industry partners, and increasingly focussing upon dissemination of the ITRC results. We will be exploring opportunities for responding to the considerable international interest in our research and the ways in which it may further contribute to UK science, engineering and global competitiveness.



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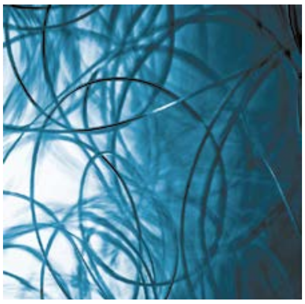

Acronyms

AD	Anaerobic digestion
BEV	Battery electric vehicle
BMW	Biodegradable municipal waste
BOD	Biological oxygen demand
C&D	Construction and demolition waste
C&I	Commercial and industrial waste
CC	Carbon cost
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CCTV	Closed-circuit television
CGEN model	Combined gas and electricity network model
CHP	Combined heat and power
DECC	Department for Energy and Climate Change
DfT	Department for Transport
EfW	Energy from waste
EHT	Electrification of Heat and Transport (Energy sector strategy)
EMR	Electricity Market Reform
EU	European Union
EV	Electric vehicle
FTA	Fast Track Assessment
FTTC	Fibre to the Cabinet
FTTH	Fibre to the Home
G2V	Grid-to-vehicle
GDP	Gross Domestic Product
GOR	Government Office Region

GVA	Gross Value Added
HD	High Definition
HP transmission	High pressure transmission
HV transmission	High voltage transmission
HWRC	Household Waste Recycling Centre
ICT	Information and Communication Technology
ISP	Internet Service Provider
ITRC	Infrastructure Transitions Research Consortium
IVC	In-vessel composting
LACW	Local Authority collected waste
LCPD	Large Combustion Plant Directive
LEB	Local Energy and Biomass (Energy sector strategy)
LINX	London Internet Exchange
LNG	Liquid natural gas
LP	Liquid petroleum
LTE	Long-term evolution
LV transmission	Low voltage transmission
MBT	Mechanical Biological Treatment facility
MDM-E3	Multisectoral Dynamic Model – Energy-Environment-Economy
MHT	Mechanical Heat Treatment facility
MPI	Minimum Policy Intervention (Energy sector strategy)
MRF	Material Recovery Facility
MSW	Municipal solid waste
NGA	Next Generation Access
NGN	Next Generation Network
NISMOD	National Infrastructure System Model
NISMOD-DB	A national database of infrastructure networks, demand and performance
NISMOD-LP	A national model of the long term performance of interdependent infrastructure systems
NISMOD-RD	A model of regional development and how it adapts to infrastructure provision
NISMOD-RV	A national model of risks and vulnerability in national infrastructure systems
NMF	Network Modelling Framework
NOx	Nitrogen oxides
Ofcom	Office of Communications (communications regulator)
Ofgem	Office of Gas and Electricity Markets (energy regulator)

ONS	Office of National Statistics
P-CE	Policy portfolio of Long-term Capacity Expansion
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
P-MI	Policy portfolio of Minimum Intervention
P-NS	Policy portfolio of New Service Planning and Design
P-SE	Policy portfolio of System Efficiency
PV	Photovoltaic
RDF	Refuse derived fuel
SRF	Solid recovered fuels
SS	Suspended solid
UKCS	UK Continental Shelf
V2G	Vehicle-to-grid
VHBC	Very High Bandwidth Connectivity
WDM	Wavelength-division multiplexing
WEF	World Economic Forum

Appendix 1 – strategy narratives

Energy headline strategies – narratives

	Strategy name	Example narrative
EN0	Minimal policy intervention	There is no significant strengthening of climate policies and therefore longer term targets are not necessarily met. Concerns about energy security continue and ensure that there is sufficient investment to ensure reasonable levels of energy security. Existing long term trends in demand continue with upward pressures from population and economic growth offset by improvements in energy efficiency, but only limited improvements in regulatory standards, some tax incentives and limited support programmes. Smart meters are rolled out, but there is no need for significant use of demand response. The energy supply sector changes rather slowly, with continued dominance of large scale investments by large companies. There is no significant investment in nuclear or CCS. Renewables investment continues as cost fall, but capacity increases only slowly. Power sector investment continues to rely largely on gas CCGTs with gas supplies from imported, but diverse, sources. Heat remains largely dependent on gas although with continued efficiency improvements. Transport remains fuel supply remains largely oil dependent with some slow penetration of biofuels and electricity.
EN1	Local energy and biomass	Concerns about energy security continue. Existing long term trends in demand are reduced as upward pressures from population and economic growth are more than offset high efficiency heating systems (heat pumps and CHPs), moderate improvements in energy efficiency, stimulated by a combination of active policies and rising awareness of energy security and need for local action. After 2020, solar PV costs fall to below grid parity and a major paradigm shift occurs, with solar energy deployment becoming mainstream for companies and households. Smart meters are rolled out. In this case there is less emphasis on demand response, but increased emphasis on consumer information and demand reduction, especially in buildings. New demands for electricity in heating and transport are more moderate. There is moderate investment in heat networks in all large urban areas. The electricity supply sector changes steadily. Initial investment is largely in wind, but in this case there is greater emphasis on onshore wind with rapid increases in the acceptance of onshore wind turbines, and much increased diversity of ownership, including by community groups, local authorities and cooperatives. These changes have implications for networks. There is increased deployment of distributed generation (although not as quickly or as highly distributed as in solar world), resulting in a more active role for electricity distribution grids. Biogas is increasingly introduced into the gas grid and takes a large share of gas demand, as total heat falls.

<table>
<tr><th colspan="3">Energy headline strategies – narratives</th></tr>
<tr><th></th><th>Strategy name</th><th>Example narrative</th></tr>
<tr><td>EN2</td><td>Electrification of heat and transport</td><td>There is a continued emphasis on strong climate policies with targets generally met. Concerns about energy security continue and are addressed by large investments in low carbon electricity generation. This ensures that there continues to be a reasonable level of energy security.

Existing long term trends in demand continue with upward pressures from population and economic growth offset by improvements in energy efficiency, but only limited improvements in regulatory standards, some tax incentives and limited support programmes. But the priority on the demand side is increased electrification of demand in heat and transport. Smart meters are rolled out and increasingly used in demand response programmes in all demand sectors.

Distributed solar PV is adoption is moderate. Transport electrification provides demand response – the energy storage capacity of vehicle batteries and building heating systems become critical for the effective management of electricity loads. This provides additional drivers for the deployment of electric vehicles and heat pumps.

There are rapid increases in the capacity of electricity grid, especially after 2030. Transmission and distribution networks are strengthened and additional transmission capacity built to bring power from offshore resources. The gas grid falls into decline and large parts are decommissioned between 2030 and 2050.

The electricity supply sector changes quickly to meet rising demand from electrification. There is very large and rapid investment in a major low carbon power generation technology, with continued dominance of large companies. Within this there are three broad options:

Option a: High offshore

There is early and rapid investment in offshore wind, primarily in the North Sea, followed by wave and tidal flow investment, mainly in the Atlantic, after 2030. Both developments are facilitated by major offshore grid extensions and strengthening of north to south transmission.

Option b: High CCS

Carbon capture and storage is demonstrated on both coal and gas power stations and rapidly becomes the preferred form of generation investment. There is rapid investment after 2030, largely on existing coal and gas power station sites, so that no significant changes in grid infrastructure are needed.

Option c: High nuclear

There is successful investment in nuclear power before 2020 and a steady growth in investment the next decade, followed by new generation 4 technologies after 2030. Investment is confined to existing coastal nuclear sites, requiring some grid strengthening.

Sensitivity analysis: High Interconnections

There is a continued emphasis on strong climate policies with targets generally met. Concerns about energy security continue, not only in the UK but across Europe. As a result there is a planned investment in a European supergrid to ensure energy security.

Large and rapid investment, especially in offshore wind, plays a key role in kick-starting EU-wide collaboration on interconnection, initially in the North Sea states, but after 2030 to accommodate very large supplies of solar PV in southern Europe.

Very large investments are made in electricity transmission, much with EU financial support. This includes new, high capacity, long distance, very high voltage, transboundary lines, but also massive strengthening of north to south transmission within the UK to take wind and marine power from Scotland to the rest of Europe.</td></tr>
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Energy headline strategies – narratives		
	Strategy name	**Example narrative**
EN3	**Gas world**	There is a weakening of climate policies and longer term targets are abandoned. Concerns about energy security continue and increase in the face of global uncertainties, placing increased emphasis on indigenous fossil fuel production. Shale gas technologies rapidly penetrate European markets, and after 2030 UK shale gas captures a major share of energy demand. Existing long term trends in demand continue with upward pressures from population and economic growth offset by improvements in energy efficiency, but only limited improvements in regulatory standards, some tax incentives and limited support programmes. There is no significant use of demand response or demand reduction. There is no significant investment in nuclear or CCS. Renewables investment declines as shale gas costs fall. Power sector investment after 2020 is entirely in gas CCGTs with gas supplies initially reliant on imported sources. After 2030 UK shale gas is the dominant source. The electricity supply sector changes rather slowly, with continued dominance of large scale investments by large companies. There is little change in grid configuration. The gas grid continues to develop and grow, both to supply new CCGTs, but also, after 2030 to transport very large gas flows from the shale gas fields in NW England to the rest of the UK. Heat remains largely dependent on gas although with continued efficiency improvements. Transport fuel supply remains initially oil dependent. After 2030 there is increased use in CNG vehicles.
EN4	**Balanced transition**	There is a continued emphasis on strong climate policies with targets met. Concerns about energy security continue and are addressed by large investments in energy efficiency and conservation, and facilitation of a balanced market competition among various microgeneration and energy sources with adequate carbon prices. Low carbon electricity generation and biomass technologies are adopted with emergence of a largely electrified economy with increasingly lesser dependence on natural gas. This ensures that there continues to be excellent energy security. Existing long term trends in demand are reduced as upward pressures from population and economic growth are more than offset by improvements in energy efficiency, stimulated by a combination of active policy and rising awareness of the need for local energy action. Smart meters are rolled out and used effectively for both demand response and demand reduction. Heating demands fall and are met by a combination of low carbon technologies, including heat pumps and CHPs. There is increased investment in heat networks in all large urban areas. Solar PV and thermal costs drop and are adopted widely. The electricity supply sector changes quickly in line with current policy plans. There is very large and rapid investment in all of the major low carbon power generation technologies. As a result the UK decarbonises supply very quickly up to 2030. Falling prices of renewables with open market competition and carbon prices, renewable technologies capture a balanced share in the energy supply mix along with gas that also provides for flexibility in a high renewable mix.

Transport headline strategies – narratives		
	Strategy name	**Example narrative**
TR0	**Decline and decay**	No replacements are found for fossil fuels, meaning that as reserves run out motorised transport increasingly becomes the preserve of the rich. Mobility reduces, with a growth in the use of slow but fuel-efficient modes (walk and cycle for passengers, canals/coastal shipping for freight) and in public transport (particularly electrically-powered systems. While substitution of travel by ICT interaction occurs, overall levels of connectivity decline.
TR1	**Predict and provide**	Demand modelling drives infrastructure construction, with large scale road building and widening programmes, airport and seaport expansion, and construction of additional railway lines. Construction determined by benefit-cost ratios, with environmental factors given a low weighting. Early schemes might include postponed road projects from the 1990s, additional runways at Heathrow, Gatwick and Stansted, the Dibden Bay container terminal, HS2 and the East-West rail link. The ongoing release of latent demand would mean that the expansion of transport networks continued throughout the century, although this could to some extent be offset by the phenomena of 'peak travel'.

Transport headline strategies – narratives		
	Strategy name	**Example narrative**
TR2	**Cost and constrain**	Environmental, financial and congestion-related imperatives mean that pricing structures are used to suppress demand on congested or sensitive corridors. Measures might include national road pricing to disincentivise travel on congested routes at peak periods, work place parking levies, above inflation increases in rail fares where trains are overcrowded, higher levels of air passenger duty, and a tax on charter flights to free-up capacity for 'higher priority' business travellers. Smartcard technology would permit a high degree of price differentiation alongside these measures to encourage travellers to shift to less-congested routes and time periods and from private to public transport. There would be minimal investment in new infrastructure, with funds focused on maintaining the existing network.
TR3	**Adapting the fleet**	Rapid technological development allows wide-ranging modernisation of the vehicle stock for all modes. Increased engine efficiencies reduce energy consumption for all types of vehicle. Electrification is extended across the existing rail network and through the development of new tram and trolleybus networks. Extensive deployment of hybrid transmissions and regenerative braking also reduce fuel consumption. Advances in materials science lead to the production of lighter construction materials, reducing vehicle weights and thereby increasing fuel efficiency. These increases in efficiency and reductions in weight allow the operation of faster, longer trains which can carry more passengers per unit of capacity than current rolling stock, and of larger aeroplanes which again reduce fuel consumption per passenger.
TR4	**Promo-pricing**	A highly differentiated and disaggregated pricing regime is progressively introduced for all modes, to ensure that transport users pay as close as is possible to the exact social cost incurred by their journey. This includes, for example: differential taxation for users of different fuels in road vehicles, with lower emission fuels incurring less tax; differential taxation for users of different modes, depending on their environmental and infrastructure footprints; national road pricing, with highly-congested roads charged at a higher rate than little-used roads; and temporal variations in pricing, with users charged more to travel at busy times. The taxes raised would be earmarked for infrastructure enhancements. Together these measures would aim to optimise capacity utilisation.
TR5	**Connected grid**	Maximum possible use would be made of ICT to enhance the operation of transport systems, with a high and increasing level of embedded technology. Measures might include: • efficient road vehicle routing, based on real time traffic information enhanced by vehicle positioning systems; • automated 'platoons' of vehicles on trunk roads to increase capacity utilisation and potentially increase maximum permitted speeds and the use of hard shoulder running; • real time road pricing based on enhanced traffic information; • cooperative traffic management systems; • flexible pathing and moving block signalling on the railways; • and smart logistics systems to optimise freight movements by all modes. Traffic data provided by crowd sourcing from mobile phones and sat navs would be used to optimise system performance. Overall traffic volumes could be progressively reduced as increased use of video-conferencing, 3D printing, ultra-high-speed internet connections and hologram-based communications reduce the need for both passenger and freight transport, fulfilling the hypothesis of 'peak travel'.

Transport headline strategies – narratives		
	Strategy name	**Example narrative**
TR6	**Smarter choices**	A national program of measures to influence and alter travel behaviour and freight logistics would use a variety of 'soft' interventions to promote more considerate and sustainable travel. This would use techniques such as workplace travel plans, targeted discounts and promotional material, and awareness-raising to promote and increase cycling, walking, and public transport use, and reduce intra-zonal road congestion. Additional measures for freight transport might include incorporate drop off boxes and consolidation centres. Substitutes for travel, particularly those based on ICT, would also be promoted (see Scenario 5).

Water headline strategies – narratives		
	Strategy name	**Example narrative**
WR0	**Current trends**	Per capita demand for water changes according to the historical trend, while connectivity between regional networks and the provision of water supply infrastructure remain unchanged from the existing configuration.
WR1	**Local resilience**	Via emphasis on the efficient use of existing water resource at the scale of existing water supply infrastructure networks, measures to reduce per capita demand through are differentially efficacious. Regions are conservative in their attempts to preserve their local water ecosystems, and prefer no further development of freshwater resources. Instead, they tend towards effluent recycling, supported by desalination. Proprietary management of water resource persists, consistent with a trend towards self-sufficiency through technology, with connectivity between regions remaining static.
WR2	**Closed loops**	Communities become increasingly feudal in their attempts to preserve what water resource is available locally: regional water supply infrastructure networks become closed loops, with per capita demand static or slowly varying about a minimally sufficient level, and no additional connectivity between regions established. The recycling of effluent becomes (or has already become) the primary means of meeting the demand for water, while prioritised investment eliminates all losses from the water supply infrastructure system.
WR3	**Local integration**	A proprietary model of water supply infrastructure management persists. External pressures prohibit abstraction from the water environment is excess of historic levels; thus, water service providers maximise the integration of strategic resources across their operational areas by enhancing the connectivity between regional water supply infrastructure networks according to existing geopolitical relationships. Prevailing water management practices persist, and per capita demand does not diverge greatly (if at all) from historical trends.
WR4	**National integration**	The declaration of a national strategy of water provision supersedes pre-existing geopolitical and commercial interests as part of a major effort to maximise the efficiencies in allocating the water resource available across the whole of the UK, subject to stringent efforts to preserve and protect the water environment that curtail the development of water resources and the abstraction of water to historical limits. The result is a targeted programme of connectivity enhancement between water supply infrastructure networks, tending towards a fully interconnected system, but a comparatively unambitious programme of demand management measures that result in changes in the per capita demand for water similar to the historical trend.
WR5	**Regional conservation**	Efforts to preserve and enhance the water environment aggravate tension between human and non-human consumers of water, as increasingly stringent abstraction controls progressively diminish the quantity of water available for abstraction, and prevailing proprietary interests continue to define the spatial scale of water supply infrastructure networks and constrain the enhancement of connectivity between regional networks. To offset these limitations, programmes of demand management decrease the per capita demand for water.

Water headline strategies – narratives		
	Strategy name	**Example narrative**
WR6	**National conservation**	A national programme of aggressive environmental conservation realised through aggressive investment in new infrastructure. Enhanced connectivity tending towards a national water grid integrates the regional water supply infrastructure networks, while an increased reliance on effluent recycling decrease the need for abstraction from the water environment. Progressive investment in demand management measures reduces the per capita demand for water.
WR7	**Local crisis**	Increases in the per capita demand for water places increased stress on the water environment. Decision makers emphasise local resilience: no additional transfers between regional networks are constructed. New abstraction and storage infrastructure are permissible; however, the quantity of freshwater available for abstraction is reduced. Therefore, desalination and effluent recycling are preferred.
WR8	**Uncontrolled demand**	The per capita demand for water increases unabated, escalating the stress placed on an infrastructure network with constrained opportunities to abstract freshwater. In an attempt to preserve the water environment, new freshwater abstractions and reservoirs occur only in hydrological regimes that maximise the reliability of the resource in the context of a national strategy, and aggressive constraints on the quantity of freshwater available for abstraction further constrain the performance of the existing infrastructure system. The primary methods of meeting both the new demand for water and any shortfall occurring as a result of reduced performance of the incumbent system, are desalination and effluent recycling; however, enhanced connectivity between regional water networks is promoted on a case-by-case basis.
Wastewater headline strategies – narratives		
	Strategy name	**Example narrative**
WW0	**Current trends**	Prevailing wastewater management strategies persist. The per capita volumetric demand for wastewater services, the biological oxygen demand of sewage, and the chemical oxygen demand of sewage remain constant, corresponding to no change in the consumptive behaviour of consumers. Sewerage service providers maintain the existing sewer network, extending and enhancing where necessary to meet the growth in demand in accordance with established behaviour. Efficiency gains follow historical trends.
WW1	**Low environmental aspirations**	The volumetric demand for wastewater services increases, as people use water inefficiently and expand impermeable areas, and volumetric capacity of wastewater treatment works increases to meet the growth in demand. Concomitant with a less conscientious approach to managing the environment, lowered serviceability targets for treated effluent decrease the cost of treating wastewater at the cost of increasing the hazard to discharging waters.
WW2	**Retrofit technologies within existing network**	Wastewater service providers continue to expand the wastewater treatment capacity on a regional basis. An unwillingness to abandon existing wastewater network infrastructure persists: although sewer networks grow to accommodate new demand, they do so in accordance with established practices, and continue to focus on the conveyance of sewage to large, centralised wastewater treatment works. The capacities of wastewater treatment works increase to meet changes in the demand for wastewater services, and new technologies gradually replace those considered obsolete as it becomes cost-effective to do so. These actions do not influence the consumptive behaviour of the population, which follows historical trends.
WW3	**Replace WWTW with new technologies**	The development of new technologies facilitates a revolution in wastewater treatment. The long-term benefits of aggressively replacing existing wastewater treatment works rapidly exceed the costs of abandonment, albeit within the context of the prevailing arrangement of sewer networks. The possibilities of micro-treatment and effluent recycling at small scales yield a decrease in the volumetric demand for wastewater services.

Solid Waste headline strategies – narratives		
	Strategy name	**Example narrative**
WE0	**Business as usual**	Existing waste, reuse and recycling targets for household, commercial & industrial (C&I) and construction & demolition (C&D) wastes are met by continuing the current trends and building new infrastructure, particularly energy from waste (EfW) and anaerobic digestion (AD) plant as required. There is a steady improvement in the performance of the waste sector and the amount of waste being landfilled continues to fall due in part to the continuing increases in landfill tax.
WE1	**High tech**	Developments in materials separation and recovery technologies mean that wastes require minimum source separation. For householders this means two bins – food & green wastes and everything else. Consumers disengage from concerns about waste & recycling but despite this, rates of recycling and composting/AD continue to rise as does the overall waste production. The materials left over from materials recovery are used for fuels in EfW plant.
WE2	**Closed loop, zero waste**	There is a significant move to industrial symbiosis with the wastes from one process providing the raw materials for another. Waste is consciously eliminated from all stages by design and products are designed for reuse, refurbishment, repair and recycling (D4R). Landfill and incineration are largely phased out being retained primarily for disposal of hazardous wastes. Producer responsibility is increased. These changes may be supplemented by moves away from consumerism to leasing. Overall waste arisings drop.
WE3	**Deep green**	There is a move from consumption to leasing with products designed for long life, easy repair and remanufacturing (D4R). Waste arisings are reduced by increasing prices for waste disposal and increasing the involvement of the third sector in refurbishing of unwanted goods. There is little investment in infrastructure and changes are driven by cultural and behavioural change. Although the outcomes may be similar to the closed loop, zero waste scenario, there is much less investment in infrastructure.
WE4	**Maximum energy**	Landfill gas continues to supply electricity to the grid but in diminishing amounts as the effects of the EU Landfill Directive is felt. Increasing energy is produced by AD and incineration. Combustible materials are banned from landfill. Growth of recycling slows as energy is prioritised.
WE5	**National plan**	Waste treatment is nationally planned rather than controlled at the LA level. This reduces the risk of construction of excess capacity and means that waste can be processed strategically depending on national needs.

NATIONAL INFRASTRUCTURE ASSESSMENT: ANALYSIS OF OPTIONS FOR INFRASTRUCTURE PROVISION IN GREAT BRITAIN

Decisions about infrastructure are long term commitments: wrong choices now could lead to future failures, and/or lock-in for future generations to inappropriate infrastructure systems, with high debts and maintenance costs and could also have important implications for sustainability. Thus we need a long term approach to analysing the options for national infrastructure provision across a wide range of plausible futures. That, however, is a complex technical task – much easier said than done. It involves understanding the drivers of demand for infrastructure services in the future and the ways in which the different infrastructure networks might cope with, and respond to that demand. The aim of the Infrastructure Transitions Research Consortium (ITRC) programme is to deliver that modelling capability for the UK.

The ITRC has now developed an integrated system-of-systems model (NISMOD) that can simulate the long term performance of infrastructure networks in Great Britain. This analysis capability has been used to compare alternative long term strategies for infrastructure provision. In total we have examined 17 different options for infrastructure provision, to be implemented over the coming decades, under a wide range of scenarios of future demographic change, economic growth and climate change. This report presents interim results from that new analysis, helping to evaluate and compare alternative strategies for national infrastructure provision. For the first time this report demonstrates how long term, cross-sectoral plans for infrastructure provision at a national scale can be mapped out and analysed.

The results reported here are interim and subject to change. ITRC analysis of national infrastructure systems continues. A book with more complete description of the methodology and results reported here will be published by Cambridge University Press in 2014. In addition, further research to improve the NISMOD model and its application to Britain's national infrastructure is planned for 2014–2015, thanks to support from the Engineering and Physical Sciences Research Council.

ITRC

EPSRC
Engineering and Physical Sciences Research Council

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