ITRC Second assessment of national infrastructure pilot results report

4TH ITRC STAKEHOLDER ENGAGEMENT WORKSHOP
JULY 2013

Summary

The ITRC has developed a 'system-of-systems' methodology to support the long term planning and appraisal of national infrastructure. The methodology is supported by a new multi-sectoral national infrastructure systems model (NISMOD). The full results of our second national assessment of infrastructure provision will be published in January 2014. This report is the first public presentation of pilot results from NISMOD and analysis of strategies for infrastructure provision that have been co-developed with ITRC's partners in industry and government.

Performance of national infrastructure strategies – There are 8 different population scenarios and a possible 72 economic scenarios. Each sector can also deploy specific strategies for future infrastructure provision. There exists a range of possible alternative strategies for each sector: energy (10), transport (7), water (9), wastewater (4) and solid waste (6). Pilot results of a limited number of strategies demonstrate important different outcomes depending on the strategy taken. For example, a low investment energy supply strategy sees an increase of carbon emissions of around 20% by 2050; whereas, a CCS strategy reduces carbon emissions 95% followed by nuclear at 90%, and offshore generation at 60% over the same period. By modelling the different strategies we can gain insight into both system level performance such as total final energy demand, carbon emissions, and sectoral level detail including operational costs associated with different technologies and levels of uptake over a long term planning horizon (2100). The range of possible strategy outcomes also implies that we may not be as locked in as we think. This should incentivise us to plan and invest into infrastructure provision over a far longer time horizon than what is conventionally done today.

Demand-driven change – It will be important to determine both the scale and timing necessary for infrastructure investment to meet growing demand. Across all of our current eight population scenarios GDP increases with a range of £2.7 – 3.7 trillion by 2050. This is coupled with higher population growth ranging from 60 – 140 million people by 2050, and continued and rising dominance of the services industry, all of which leads to increased demand for infrastructure provision. The implication is that future investment will need to ensure adequate provision of infrastructure services to those regions with projected future growth. Depending on the infrastructure type, this may require the construction of new assets in these regions or, alternatively, an expansion of carrying/transmission capacity from other regions. Assessing the different patterns of demand growth is central to the work of ITRC and is captured in our ability to model different macroeconomic and population scenarios, and how this impacts upon infrastructure provision for each sector.

ICT integrated systems – Current trends indicate an increased uptake of information and communication technologies (ICT) across sectors. An impact of ICT is that it cuts across supply and demand and will therefore shape investment needs for capacity provision and potentially alter future demand trends. The pilot model runs have so far focused on a limited number of strategies. But there are strategies within each sector that embed assumptions about increased uptake of ICT. The next round of model runs will draw this out more explicitly and consistently across each sector, and attempt to assess the system wide impacts of ICT. Future work will also assess how ICT might be a focal point to analyse interdependencies between each sector. One way forward is to assess the evidence base on ICT impacts upon each sector and re-parameterize the models to simulate efficiency improvements. However, a potential barrier might be the lack of evidence for ICT impacts upon other sectors. This will need to be further explored. The central point is that the ITRC recognizes the importance of ICT and will seek to better integrate this into our modelling capability.

Contents

1 Introduction

ITRC delivers research, models and decision support tools for the analysis and long term planning of a robust national infrastructure system. These tools address challenges for the energy, transport, water, waste and ICT systems sectors. The research programme is punctuated by 3 cycles of national infrastructure assessment, and implemented by ITRC researchers working closely with stakeholders in government, industry and academia. Cycle 1 – the Fast Track Analysis (FTA) – looked at possible futures for infrastructure in the UK, with emphasis on the drivers for change and the sources of uncertainty. It was completed in January 2012. Cycle 2 (2012/2013) tests the performance and robustness of long-term strategies for national infrastructure provision across a range of future scenarios, making use of the National Infrastructure System Model (NISMOD) developed by ITRC over the last two years.

Building on the foundations laid by the FTA, the second national infrastructure assessment reports on the 1) full development of each sector model i.e. technical specification and functionality, 2) the methodological procedure for scenario and strategy development and selection, 3) model implementation of the full range of sector specific strategies, 4) and key cross sector messages and analysis arising from the sector modelling results.

The Cycle 2 Assessment will culminate into a book called 'Planning Infrastructure for the 21st Century: System of systems methodology for analysing society's lifelines in an uncertain future' to be published by Cambridge University Press in early 2014. This book will be a major milestone not just for ITRC but for setting the global research agenda around integrated infrastructure systems planning and assessment. The book's objective is to provide its' targeted audience of practitioners, decision-makers, and academics with the concepts, models and tools needed to identify and test robust, sustainable, and resilient strategies for the provision of national infrastructure. While the analysis will be based on the UK context the goal is develop transferable lessons applicable to a variety of geographical contexts and problem domains across developed and emerging economies.

The objective of this report is to:

- Provide an update on progress, and showcase the current ITRC modelling capability;
- Report back on pilot results from the modelling teams including: 1) demographics and population, 2) economics, 3) energy demand, 4) energy supply, 5) transport, 6) water, and 7) waste;

- Develop key cross sector messages arising from pilot results;
- Outline next steps for the cycle 2 assessment.

This report proceeds with 1) an overview of the ITRC systems modelling framework including our scenario and strategy generation process, sector modelling capability, and integrated database, 2) pilot results for future demand scenarios 3) pilot results for sector strategies and 4) emerging cross cutting messages and next steps.

2 Systems modelling framework

2.1 SCENARIO GENERATION PROCESS

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 & 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.

As part of this modeling activity, we have developed an ensemble of national infrastructure 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, and we have produced a range of possible future trajectories based on this ONS data.
- 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. For Cycle 2 of the ITRC study, data for future projected UK climate change (seasonal temperatures, rainfall, sea-level rise) are given by UKCP09[1] emissions scenarios and based on the IPCC Special Report on Emissions Scenarios (IPCC, 2000).

These scenarios are then used as direct data inputs for each sector modelling team ensuring consistent assumptions are used for each sector.

1 http://ukclimateprojections.defra.gov.uk/

2.2 STRATEGY GENERATION PROCESS

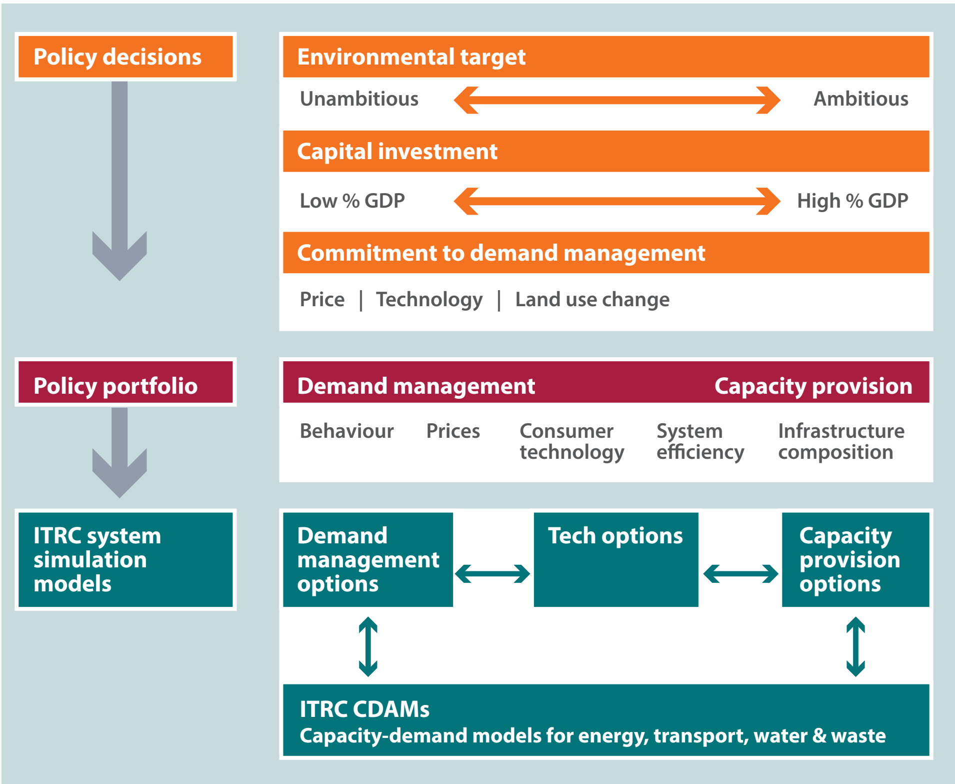
There are many possible strategies for the provision of future infrastructure services. Strategies may combine measures to increase the structure or capacity of national infrastructure networks and manage demand. Supply and demand-side measures are becoming increasingly integrated for example through 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 introduced by input variables representing 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).

This separation of changes to the system through decisions (strategies) and external future conditions (scenarios) enables us to evaluate the performance of infrastructure systems based on the specific strategy chosen across a wide range of possible future scenario conditions.

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 environmental ambition to decarbonise and mitigate other environmental impacts resulting from infrastructure operation, and the level of commitment to demand management via strong price signals, consumer technology, level of decentralisation. Figure 1 illustrates the ITRC guiding hierarchy for strategy generation consisting of high-level policy dimensions, types of changes to the infrastructure system, a portfolio of policy options, and model implementation of these options.

Figure 1. Illustration of the strategy generation process, starting from high-level policy dimensions (environmental ambition, capital investment, demand management), over the different types of changes within the different sectors, down to interpretations of types of change through use of single options.



Strategies can broadly target 1) demand management and 2) capacity provision summarized as follows:

Demand management 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 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 – 11 strategies which are accompanied by narratives listed in Appendix 1. The current report provides preliminary results for a limited number of strategies for each sector. Our next steps will focus on model implementation for all remaining strategies. Strategies in each sector are being combined and harmonised across sectors, so each infrastructure sector provides the 'building blocks' for development, for the first time, of integrated cross-sectoral strategies for infrastructure provision.

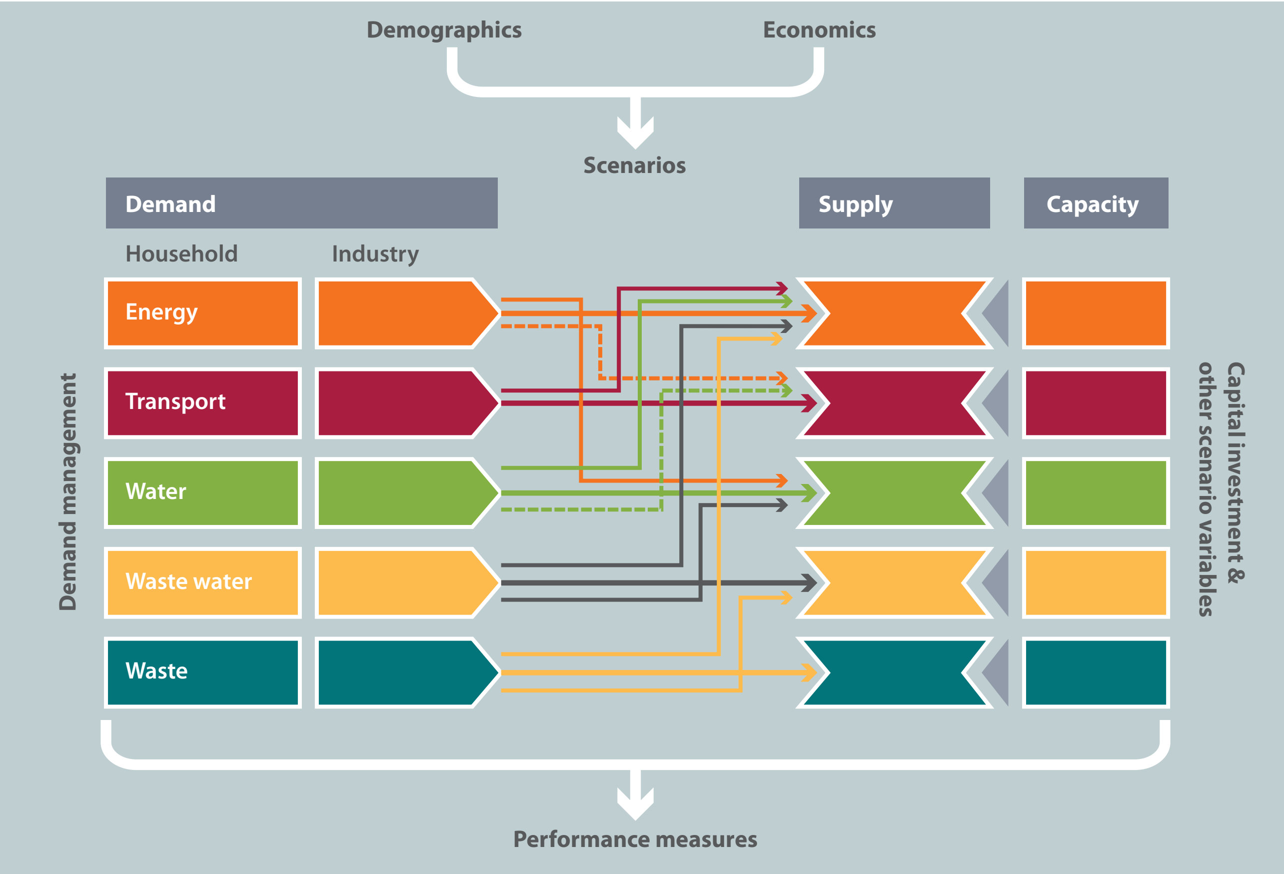
2.3 CAPACITY-DEMAND MODULES

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).

Strategies are modelled in each sector by changing input variables representing social and behavioural change (incorporated as demand management options), technological change (incorporated as changes of efficiencies and technology-cost parameters), and systemic change within the physical system of infrastructure assets (incorporated directly in the networks and impacting on capacity or incorporated via investments into assets).

Exogenous changes to the national infrastructure system are represented by scenarios of socio-economic variables, climate variables and other technological variables that are seen to be outside of the influence of any 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. This separation of changes to the system through decisions (or strategies) and external future conditions (scenarios) enables the evaluation of infrastructure system performance conditioned by a predefined strategy and influenced by a wide range of possible future conditions.

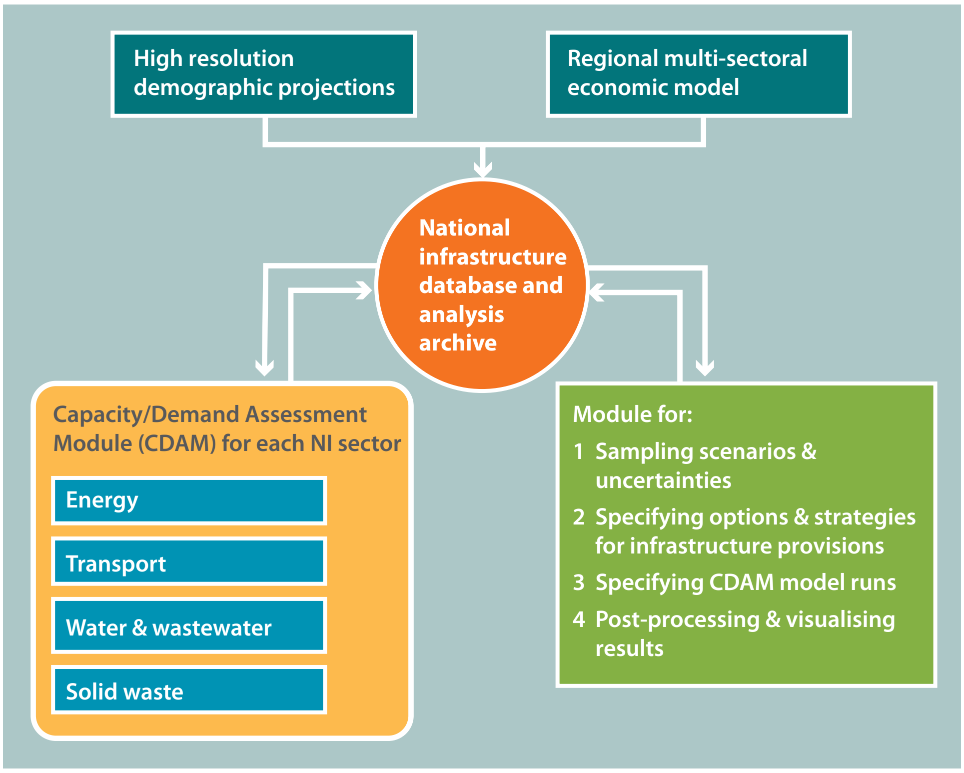
Figure 2. Framework for Capacity – Demand modules depicting flow of information and data.



2.4 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. Importantly, this integrated framework allows us to identify and assess cross-sector strategies and evaluate important trade-offs for decision making. Figure 3 illustrates how the various modelling components are linked together.

Figure 3. General architecture framework linking models, database, visualisation and analysis.



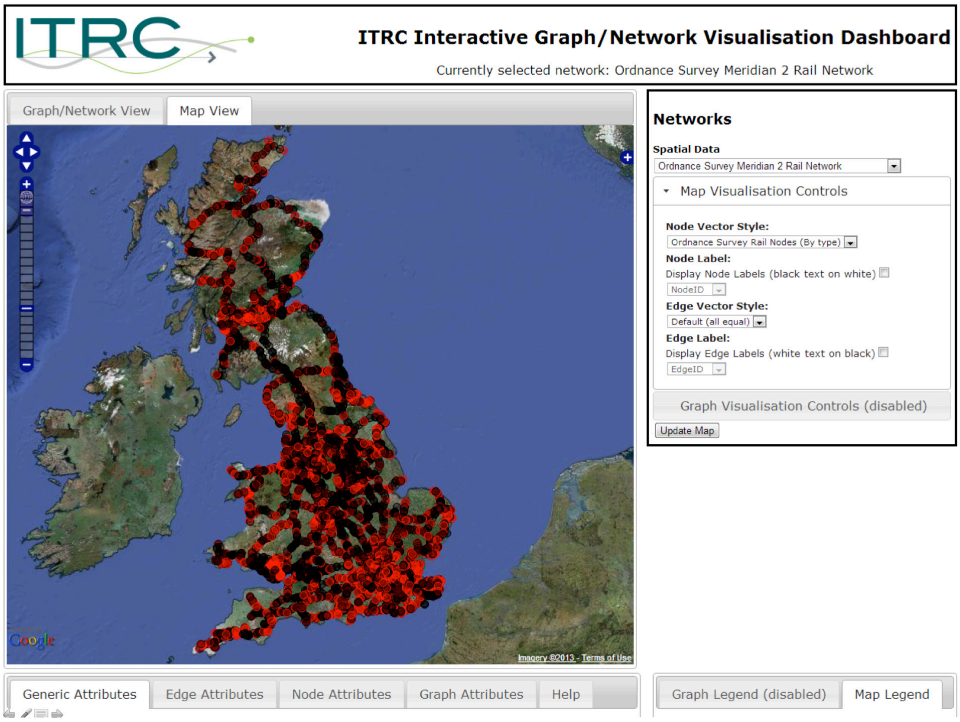
The role of the general framework is to combine the different sector modules within a linking architecture to evaluate the strategies of infrastructure provision for a consistently sampled set of future scenarios. To achieve this, the general framework provides a common input/output format for the interface between the modules and an order of solving the different modules that acknowledges the selected one-way dependencies between the modules (e.g. capacity modelling receives demand information, etc.).

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).

The dashboard is 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 allows 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 data base integration and visualisation capacity for each sector, where data outputs (demographics, population, 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 Scenarios of infrastructure demand

The following provides preliminary model results for a limited number of population and economic scenarios that are then used as inputs for each sector modelling team (Section 4).

3.1 POPULATION & DEMOGRAPHICS

3.1.1 APPROACH

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. Drivers of population change are products of economic, political and social forces, which can be described by scenarios exploring prosperity, sustainability and isolation.

Scenarios have been formally specified factoring in a 'high' or a 'low' dimension with model drivers (fertility, mortality and migration) changing accordingly. For example, low mortality would be expected under a high prosperity scenario, with the opposite occurring with low prosperity. It is necessary to estimate the extent to which each scenario dimension will influence the model drivers both in scale and direction. For example, zero implies no relationship (the dimension has no influence over the model driver) and +/-1 indicates a strong positive or negative influence. For instance, life expectancy is expected to be strongly and positively influenced by prosperity and hence has a value of 1.0. On the other hand, fertility is unlikely to be influenced by national environmental sustainability policies so has values of 0.

We have developed three scenarios, each with a high and a low dimension resulting in a total of 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.

3.1.2 RESULTS

Figure 5 illustrates the change in total population up to 2100 under the different scenario conditions. Scenarios a – d all assume high prosperity and generally predict higher population growth than the ONS baseline projection. Scenarios b and d, in particular, show considerably higher population growth which is driven by migration as they are both non-isolationist scenarios. Conversely, scenarios e – h, which are all low-prosperity scenarios, exhibit lower population growth than the ONS baseline scenario.

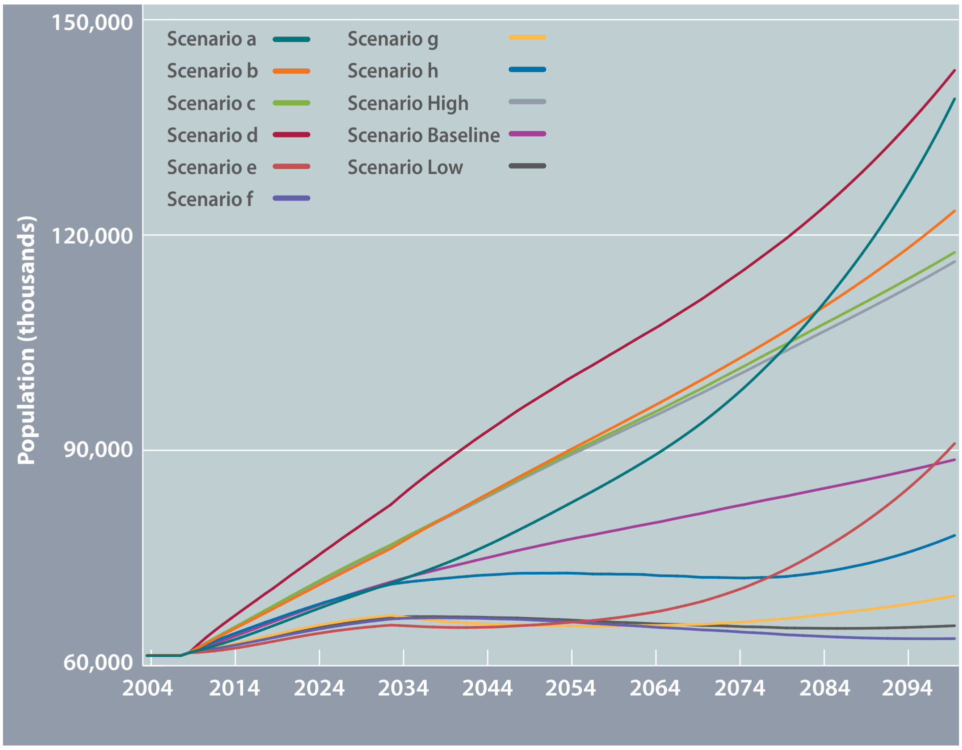


Figure 5. Total population change for 8 scenarios (d – highest; f – lowest) compared against ONS high, low and baseline projections to 2100.

Our population scenarios are able to produce a range between 60 – 140 million by 2100. Our low of ~60 million is similar to ONS projections but 4 of our scenarios are higher than the highest ONS projection of nearly 120 million by 2100. We are therefore able to accommodate a greater range of population scenarios compared to current ONS projections over the long term. For each scenario we are also able to show a time series of change in population age distribution shown in Figure 6.

Each national level population scenario can be scaled down to Government Office Regions (GORs) (and further disaggregated into Local Authority Districts (LADs)) shown in Figure 7 with corresponding changes in urban areas shown in Figure 8.

Figure 6. Time series of population distributions for high population scenario D (top row) compared with low population scenario F (bottom row) for 2010, 2050 and 2100.

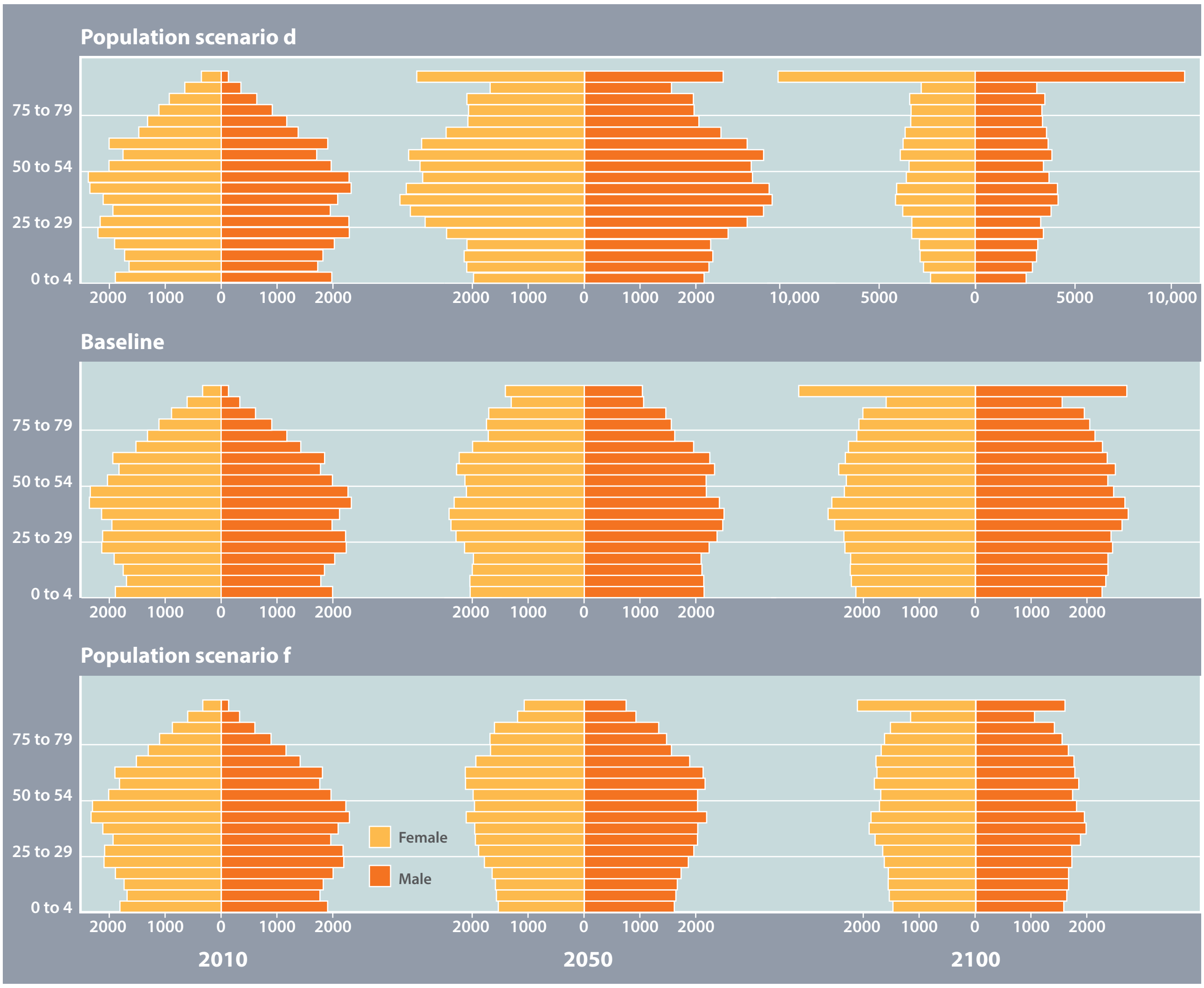


Figure 7. Change of population for eight different scenarios (a – h) (2004 – 2100).

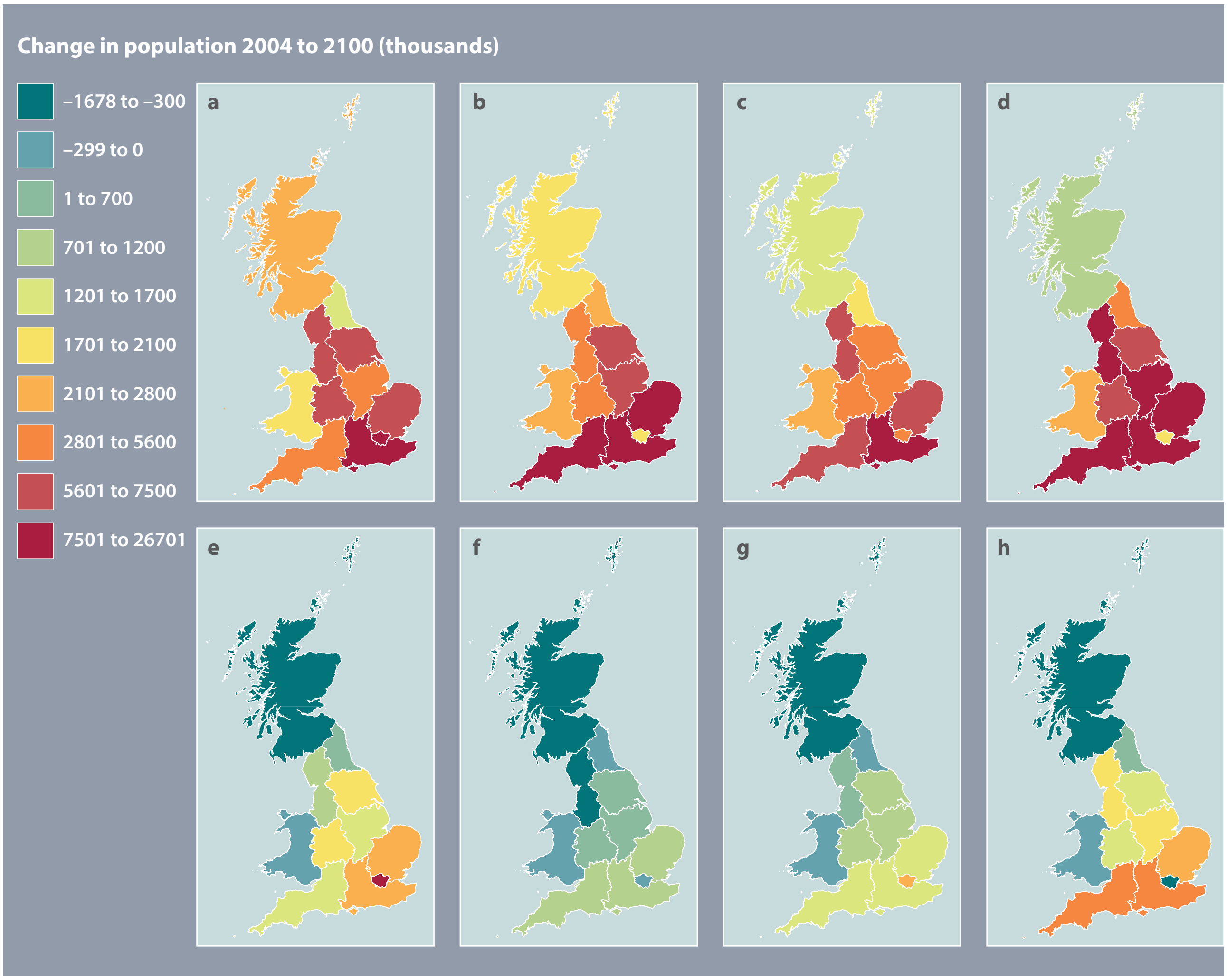
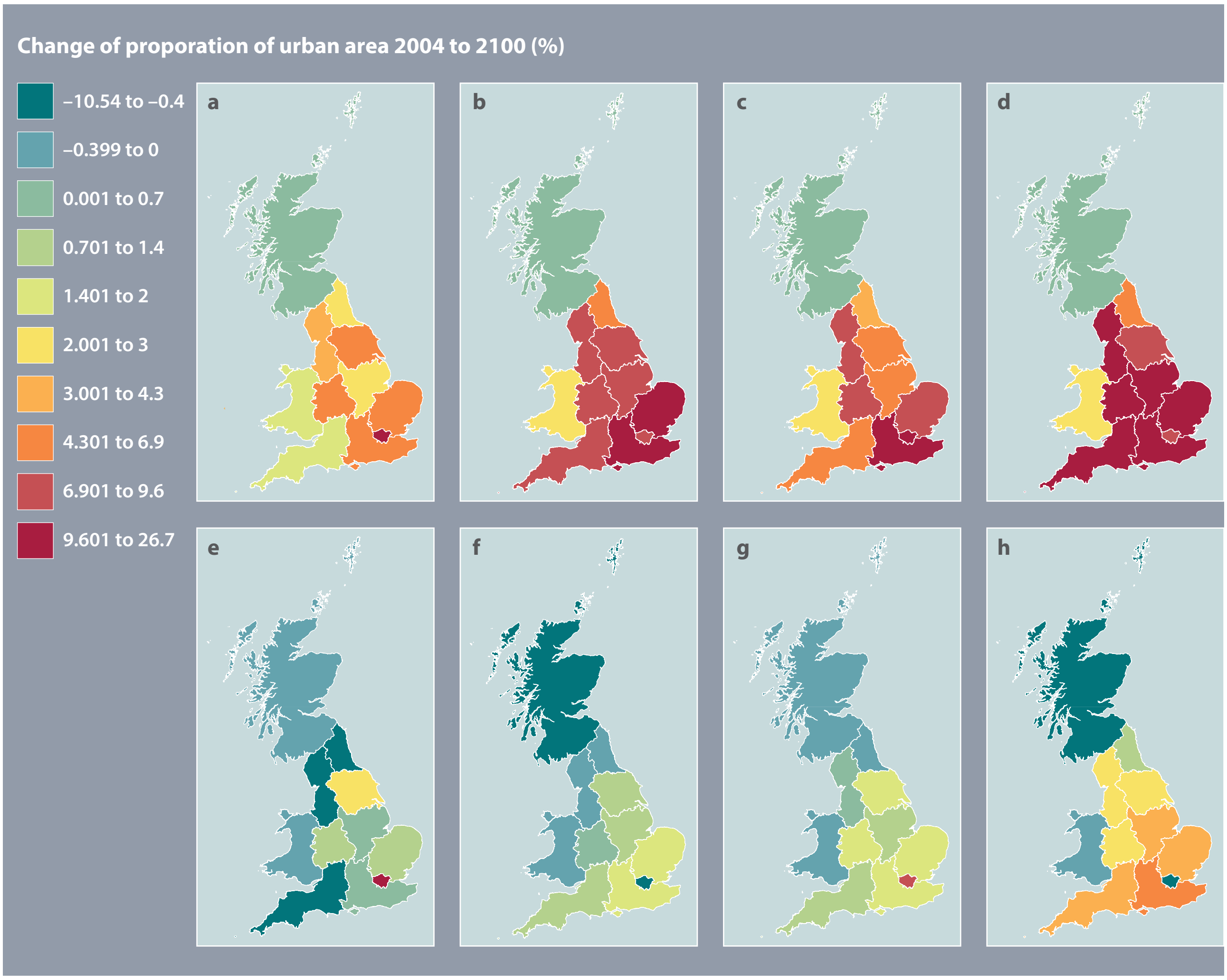


Figure 8. Change of proportion of urban area corresponding to each population scenario (a – h) (2004 – 2100).



Apart from the 8 scenarios described above, new scenarios can also be generated to simulate balanced urban growth outside London and the South-East. For example, we can assume a higher prosperity, higher sustainability and more liberal policies applied in the northern regions of Great Britain (North West, North East, Yorkshire and Humber, Wales and Scotland, denoted as North); while in the other regions (denoted as South), a policy with a baseline prosperity, sustainability and lower isolation is applied. Under these assumptions more rapid population growth could occur in the North West regions resulting in negative net migration out of London by 2020. This could imply for example, a desire to move out of London due to increasingly high population density. It will be important to explore a greater range of alternative scenarios and assess new possible trends in population growth and migration and how these impact infrastructure service provision for each sector.

3.1.2 KEY INSIGHTS

- Variations between three major scenarios are substantial. In the high scenario, population grows 4.5 million over 25 years and 21 million over 75 years over and above the central case. Over time, increasing fertility and in-migration for family age groups accelerates growth. In the low scenario, population change is initially sluggish and becomes negative after 2033;
- Generally, the population of South East Great Britain is growing faster than the North West in all of the 8 scenarios; However, two scenarios (Scenario g and h) lead to higher population growth in the North West compared to surrounding areas (i.e. Yorkshire and Humber and North East);
- Migration policy has a considerable impact on regional population trends, especially for London. More conservative policies (Scenarios a, c, e, g) could lead to higher population growth in London compared to surrounding GORs, while for more liberal policies (Scenario b, d, f, h) population growth in London is lower compared to surrounding areas (i.e. South East, East of England etc.);
- Due to the linear relationship between population density and proportion of urban area, urbanisation follows a similar trend to population growth[2];
- The current method can be used to generate additional scenarios capturing a wider range of possible population, demographic and urbanisation futures.

3.1.3 LIMITATIONS AND NEXT STEPS

- The projection model simplifies the migration variables to a general net migration value. Therefore, the model cannot precisely represent the relationship between policy scenarios and the inter or, intra-regional migrations. This means for each Local Authority District (LAD), we know the change of population due to migration but not where people are from and where they are moving to. It is expected that greater resolution will be achieved in WS3 and used to inform our modelling capability.
- All of the demographic projections are subject to the influence of government policy and other external influences at local, national and global scales. For example, border controls or quotas could influence migration; while investment in medical research and health care facilities could affect life expectancy. Fertility rates are understood to be affected indirectly by the performance and outlook for the economy. Regional housing policy could strongly determine local demographics, which might ultimately be responsive to infrastructure effects such as the availability of water or congested transport networks. These feedbacks will be explored further in Work stream 3 of the ITRC project.

---

2 A linear model was built to estimate the proportion of urban area from the population density. The method included: 1) calculate total area and 'urban' area for all LADs (e.g. using OS data), 2) regression of population density against proportion of urban area, 3) use the regression to estimate percentage urban area and hence urban density as population density changes under projections (R2 = 0.9727).

3.2 MACROECONOMICS

3.2.1 APPROACH

Economic scenarios have been generated from Cambridge Econometrics' (CE's) MDM-E3 model of the UK economy[3]. 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; 3 variants are used including: 1) 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; 2) 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 1.

Table 1. 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.

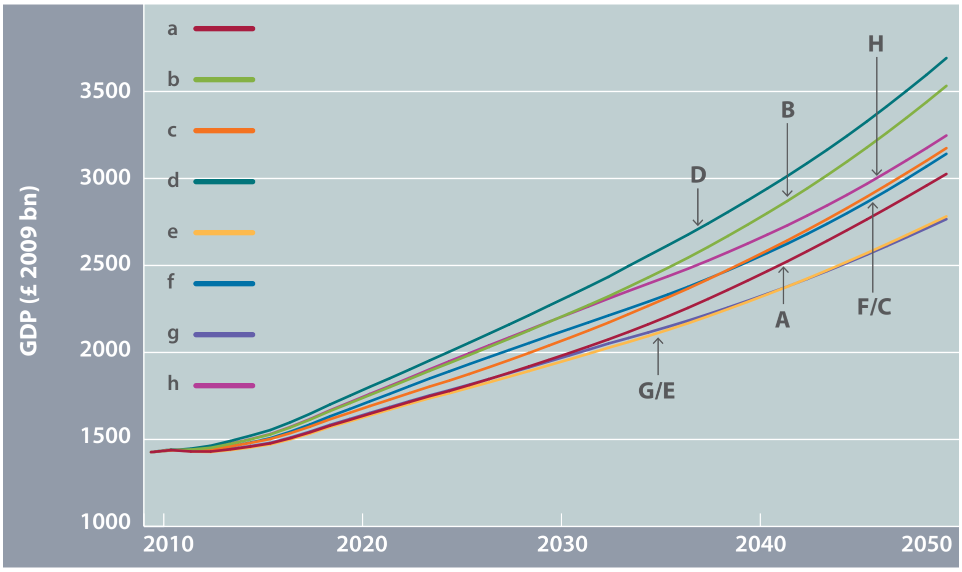
3.2.2 RESULTS

Figure 9A 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 across scenarios is ~£2.7 – 3.7 trillion by 2050. E and G scenarios have a lower GDP of 8% less than the central case A. The highest scenario D generates a GDP outcome 22% higher than A.

Figure 9B shows the range of employment outcomes from the population scenarios, which mirrors the GDP results. Compared to the A scenario, employment in E and G scenarios is 4% lower in 2050 whereas, in the D scenario employment is 11% higher.

3 Multisectoral Dynamic Model, Energy-Environment-Economy: http://www.mdm-e3.com

Figure 9. A (top) Gross Domestic Product (GDP), and B (bottom) employment results for each population scenario (2010 – 2050).



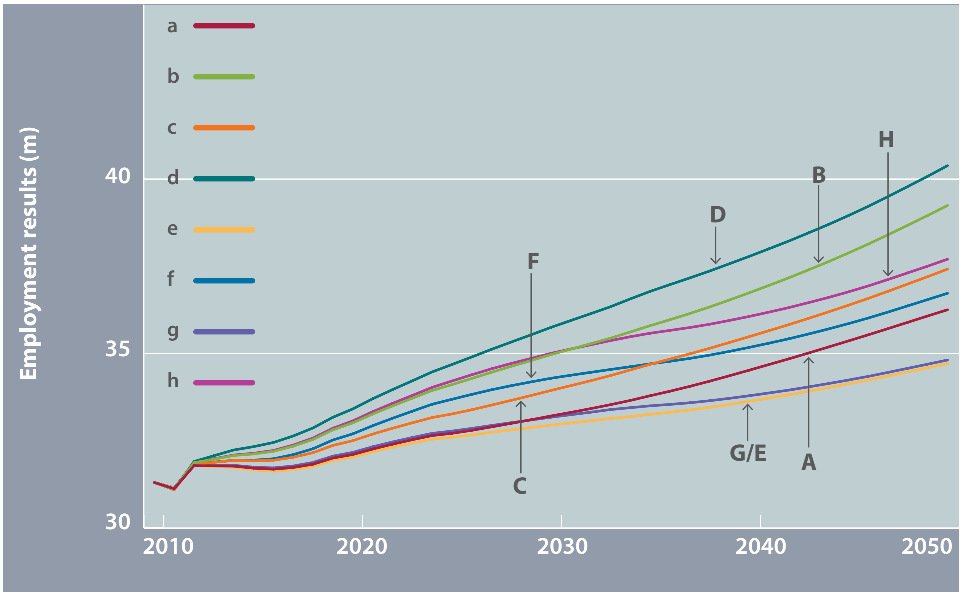
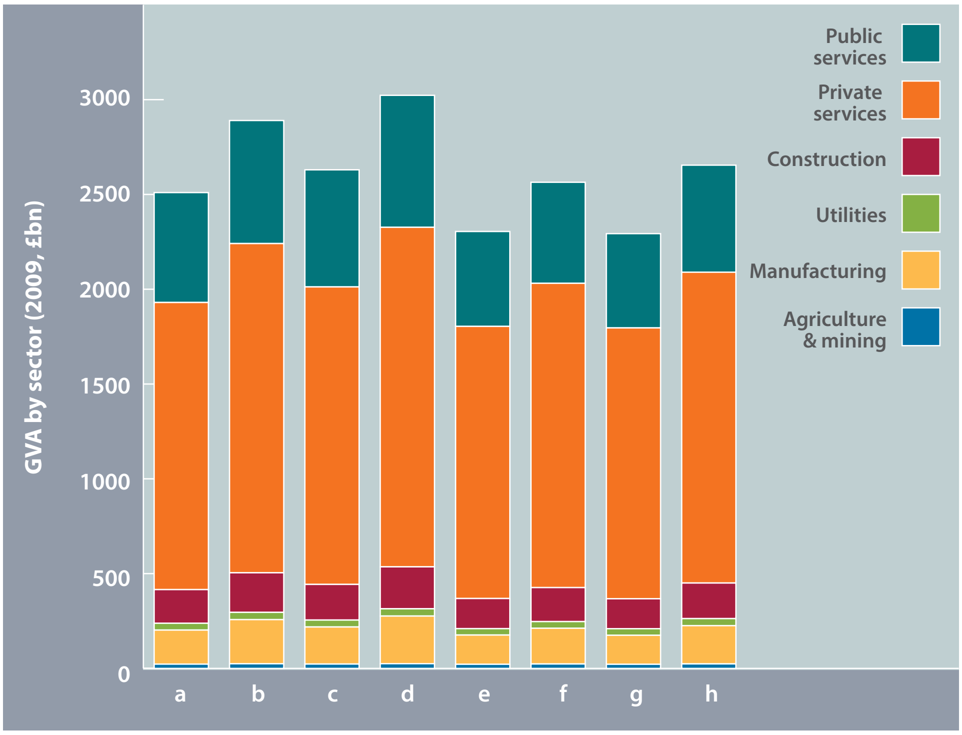
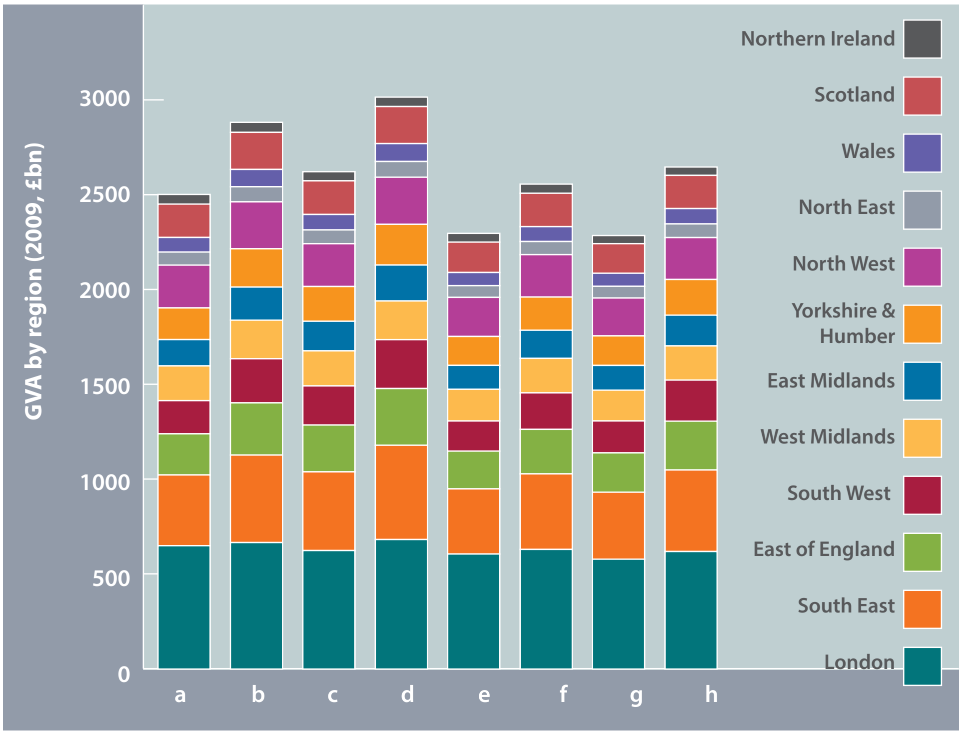


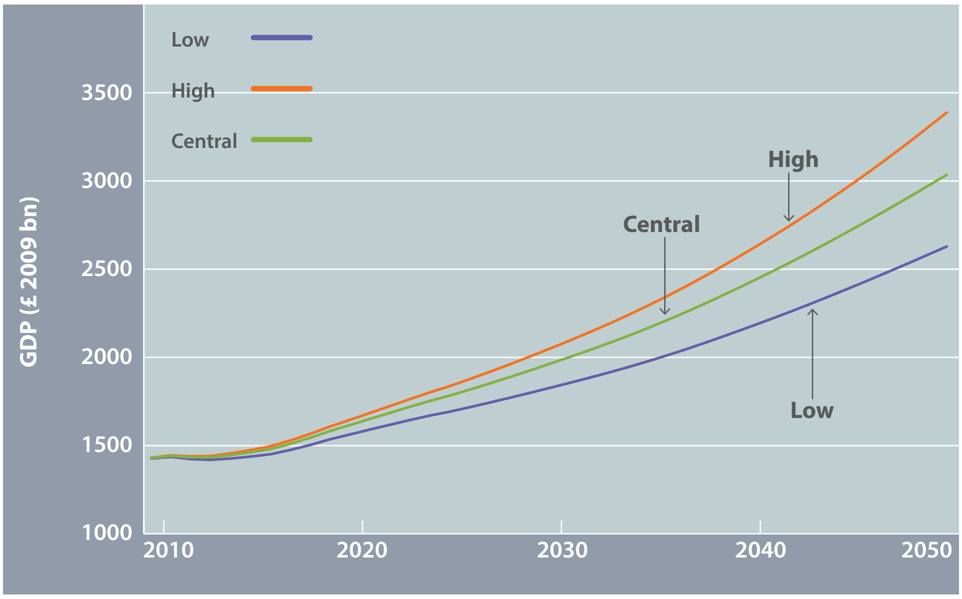
Figure 10. A (top) Breakdown of Gross Value Added (GVA) by sector and B (bottom) region for each population scenario in 2050.





By 2050, Figure 10A shows that economic activity is related to high levels of services. We can also show the regional distribution of this economic activity (Figure 10B). In terms of spatial distribution of the population, 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 services-related does not differ substantially across our current scenarios. However, more extreme variants of the distribution of regional population can be explored to assess different trends in infrastructure demand. We discuss the potential implication of this in our cross sector messages (Section 5).

Figure 11. A (top) Gross Domestic Product (GDP) and B (bottom) employment results from world economic growth scenarios (2010 – 2050).



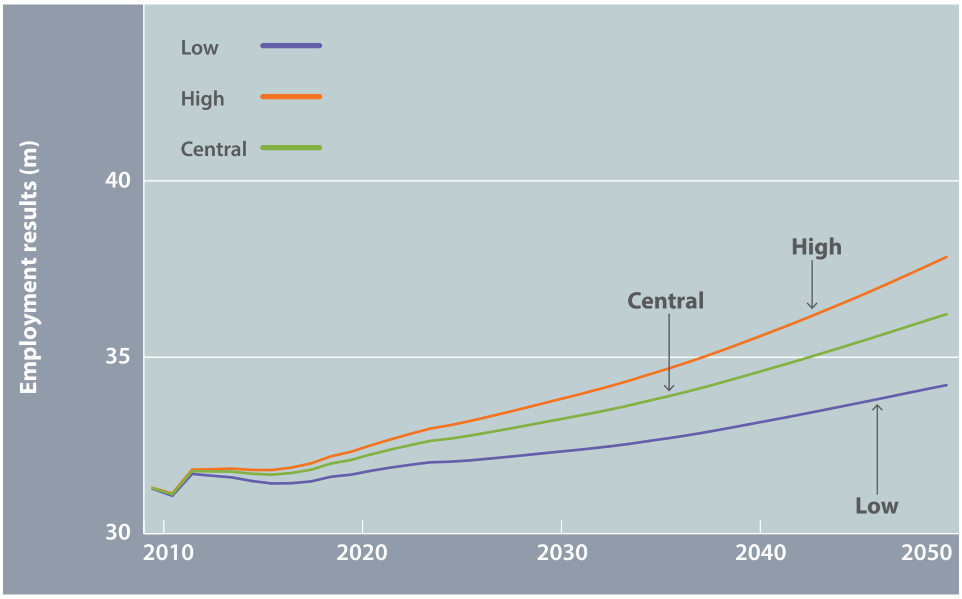
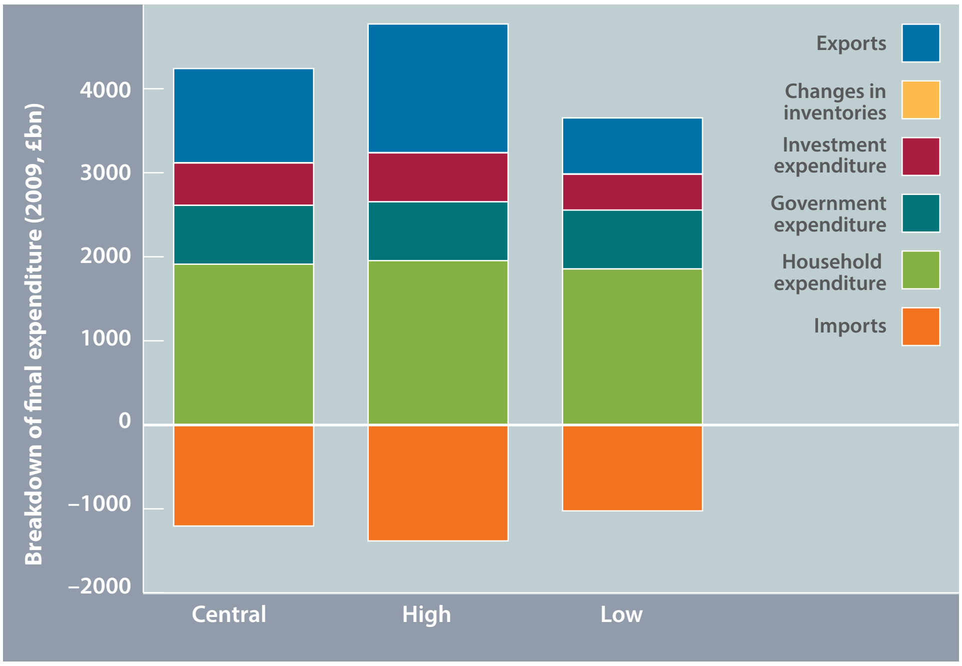
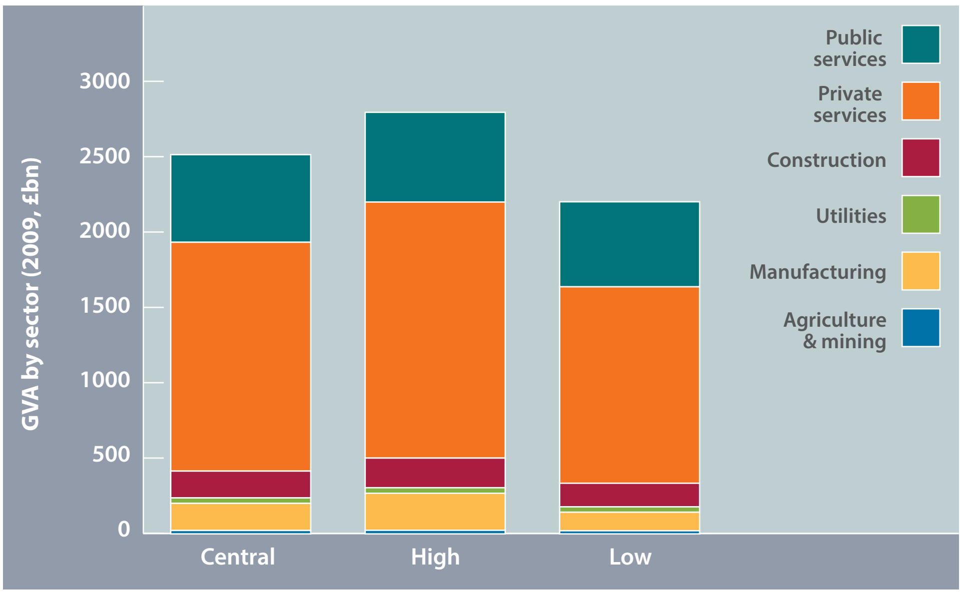


Figure 11A shows the GDP profiles from the three world economic growth variants. These are based on the central case population and fossil fuel price scenarios. Results indicate that by 2050, the difference in GDP between the Central and High scenario is 12% while the difference between the Central and Low scenario is 13%. Figure 11B shows the corresponding results for employment. The overall range of employment outcomes from alternative world economic growth is 11% compared to a range of GDP outcomes of 29%.

Figure 12A shows the breakdown of GDP by final expenditure indicating that the changes in world economic growth drives 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 contribute to the differences across scenarios, as indirect impacts. Figure 12B 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 12. A) Breakdown of final expenditure and B) Gross Value Added (GVA) by sector for each world economic growth scenario in 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 and we do not dwell on them here, although the results are available in the complete set of runs.

3.2.3 KEY INSIGHTS

- 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;
- World economic growth (outside of the UK) affects UK economic performance through changes in demand for UK exports. Thus, changes in this assumption set tend to produce stronger direct changes in manufacturing rather than services, although the UK is projected to remain a services-oriented economy in 2050;
- All possible combinations of assumption sets (population, world economic growth, and fossil fuel prices) gives 72 possible economic scenarios for direct input for sector modelling teams. This shows the breadth of possible future projections we are able to develop and assess the resulting impacts for each sector;
- GDP increases with a range of ~£2.7 – 3.7 trillion, coupled with higher population growth of 60 – 140 million people by 2050, and continued dominance of the services industry leading to increased demand for infrastructure provision. It will be important to determine both the scale and timing necessary for infrastructure investment to meet growing demand. Assessing the different patterns of demand growth is central to the work of ITRC and is captured in our ability to model different macroeconomic and population drivers and how these drivers might impact upon infrastructure provision for each sector.

3.2.4 LIMITATIONS AND NEXT STEPS

- Energy prices were identified in the FTA as a key driver across the various infrastructure sectors and this continues to be accounted for in the economic projections. The range of fossil fuel-price assumptions currently used is relatively narrow in macroeconomic terms. However, the selected range is from an official set of projections. The model shows that in aggregate the UK economy is not particularly responsive to energy price changes, but at the sectoral level might be important;
- A potential next step is to develop alternative fossil fuel price scenarios to test sensitivity at the sector level. The current set of assumptions assume flat energy prices after 2030 (in real terms), in line with several existing studies on the long-term performance of the UK energy system. To examine a wider range of long-term energy-price profiles, the most straightforward option would be to extrapolate the growth in the DECC energy prices, either from 2030 onwards (the final year for which assumptions are available), or from 2020 onwards (in some cases, the DECC assumptions are flat from 2020 onwards). Options for examining a wider range of prices could be assessed in due course.

4 Analysis of strategies for national infrastructure performance

4.1 ENERGY DEMAND

4.1.1 APPROACH

The energy sector currently has 10 strategies which share common assumptions between supply and demand summarized in Table 2. Five of these strategies are designed to represent major supply side changes with minimal cross-strategy changes in demand.

Energy demand modelling in ITRC 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 ITRC 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/or economic output) and sector strategies (Table 2).

We currently report back pilot results for only the UK industrial energy demand model. The current UK industrial energy demand model can be used to investigate:

- Energy efficiency measures in motors, lighting, refrigeration and compressed air across the entire industry sector;
- Best Available Techniques (BAT) in terms of best in class or cost-effectiveness, and emerging additional, or replacement technologies for 5 energy intensive sectors in the UK (iron and steel, cement, pulp and paper, chemicals, food and beverages). Currently, technologies in 2 sectors (cement, iron and steel) are implemented;
- Fuel switching and energy reuse options in low temperature heat (<300°C) and space heating. Fuel switching technology options used are industrial gas boilers, heat pumps, and gas/biomass combined heat and power (CHP) options are also available;
- Other fuel/sub-sector specific energy efficiency improvements such as boiler insulation, voltage optimisation, metering etc.

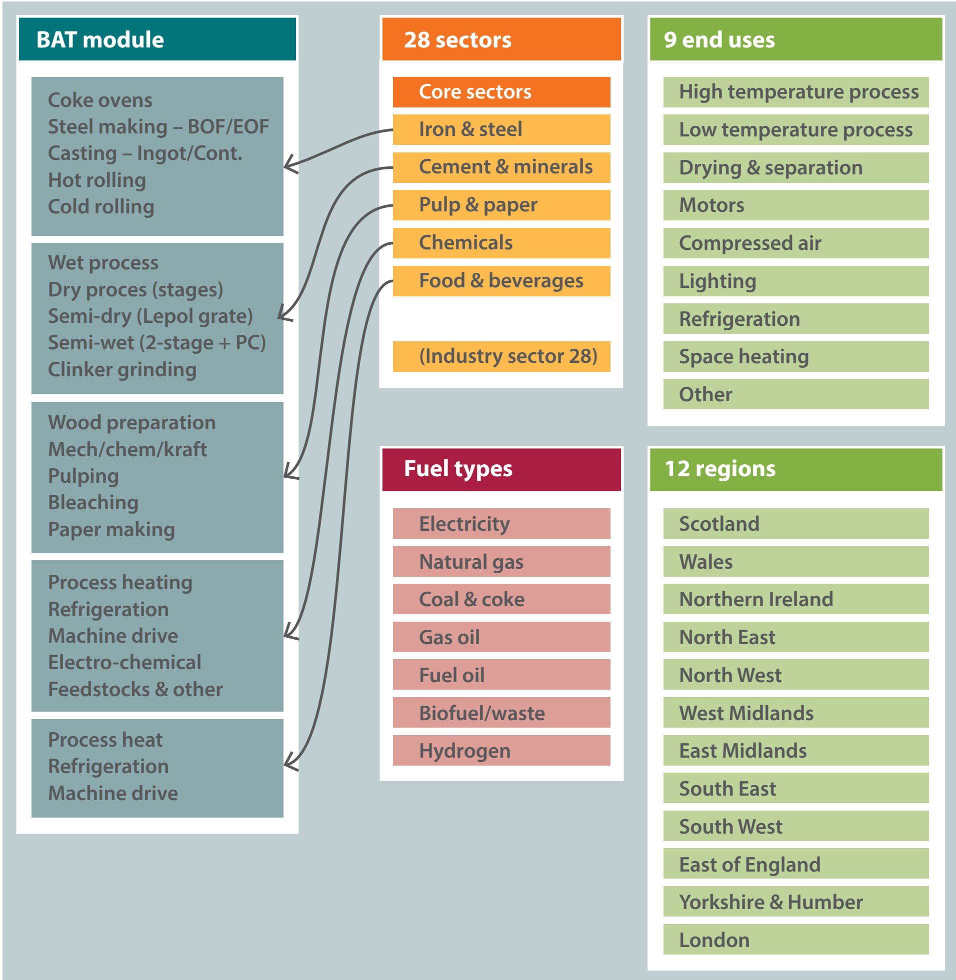
Table 2. Energy demand and supply strategies

	Strategy name	Demand change	Structural change	Capacity/Supply change
EN0	Minimal policy intervention	ED0 – No change	ES0 – No change	EC0 – No change
EN1	Central electric, flexible consumer	ED3–Demand response	ES0 – No change	EC2a,b,c – High electricity futures
EN2	Solar world	ED2–Demand reduction	ES3 – High distributed storage	EC4 – High solar
EN3	Local energy & biomass	ED2 – Demand reduction	ES2 – Distributed generation and heat	EC3 – Biofuel nation
EN4	Interconnected world	ED1a,b – Electrification	ES1 – High interconnection	EC2a – High offshore and marine
EN5	Gas world	ED0 – No change	ES0 – No change	EC1 – Dash for gas
EN6	Local hydrogen	ED3 – Demand response	ES4 – Decentralised hydrogen	EC2a – High offshore and marine
EN7	Electrification of heat and transport	ED1a,b –Electrification	ES0 – No change	EC2a – High offshore and marine EC4 – High solar
EN8	Nuclear & gas	ED0 – No change	ES0 – No change	EC1 – Dash for gas EC2c – High nuclear
EN9	All in – diverse low carbon (comparable contributions from listed options)	ED1a,b- Electrification ED3 – Demand response ED2 – Demand reduction	ES3 – High distributed storage ES2 – Distributed generation and heat	EC2a – High offshore and marine EC4 – High solar EC3 – Biofuel nation

See Appendix 1 for strategy narratives.

Yearly energy demands are estimated by sub-sector, region, end-use and fuel type, and can be aggregated and visualised in any combination of these attributes. Currently, the model has 28 sub-sectors, 9 end-uses, 12 regions and 6 fuel types (electricity, gas, oil, solid fuel, bioenergy, hydrogen) shown in Figure 13.

Figure 13. Disaggregation level of Industry demand model.



4.1.2 RESULTS

The following pilot results are for the industrial energy demand model only. Additional outputs will follow after the remaining energy demand models are fully developed. Figure 14 shows the impact of economic growth (GDP) on industrial energy use by comparing energy consumption per sector under a high GDP scenario for a low investment strategy (Minimum Policy Intervention (MPI)) compared to a high investment strategy (All-in). The MPI strategy assumes 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, with the energy supply sector changing slowly. In contrast, the All-in strategy assumes rapid changes in the electricity supply sector led by heavy investment into demand reduction, low carbon generation, and biomass technologies. As a result the UK decarbonises energy supply very quickly up to 2030.

Figure 14. UK industrial energy demand by sector under a high GDP growth scenario (2010 – 2050: A) Minimum Policy Intervention, and B) All-in strategy.

Holding GDP effects equal we can see an important difference in performance outcomes based on what strategy is taken. The All-in strategy results in a 23% decrease in final industrial energy consumption by 2050 as compared to the low investment MPI strategy. This is a non trivial result given that overall energy reduction opportunities in industry are generally viewed as limited since the current stock of industry technologies are reaching their thermodynamic potential. The high investment strategy therefore supports the case for greater de-materialisation and re-use in industries to decouple industrial energy use and economic growth.

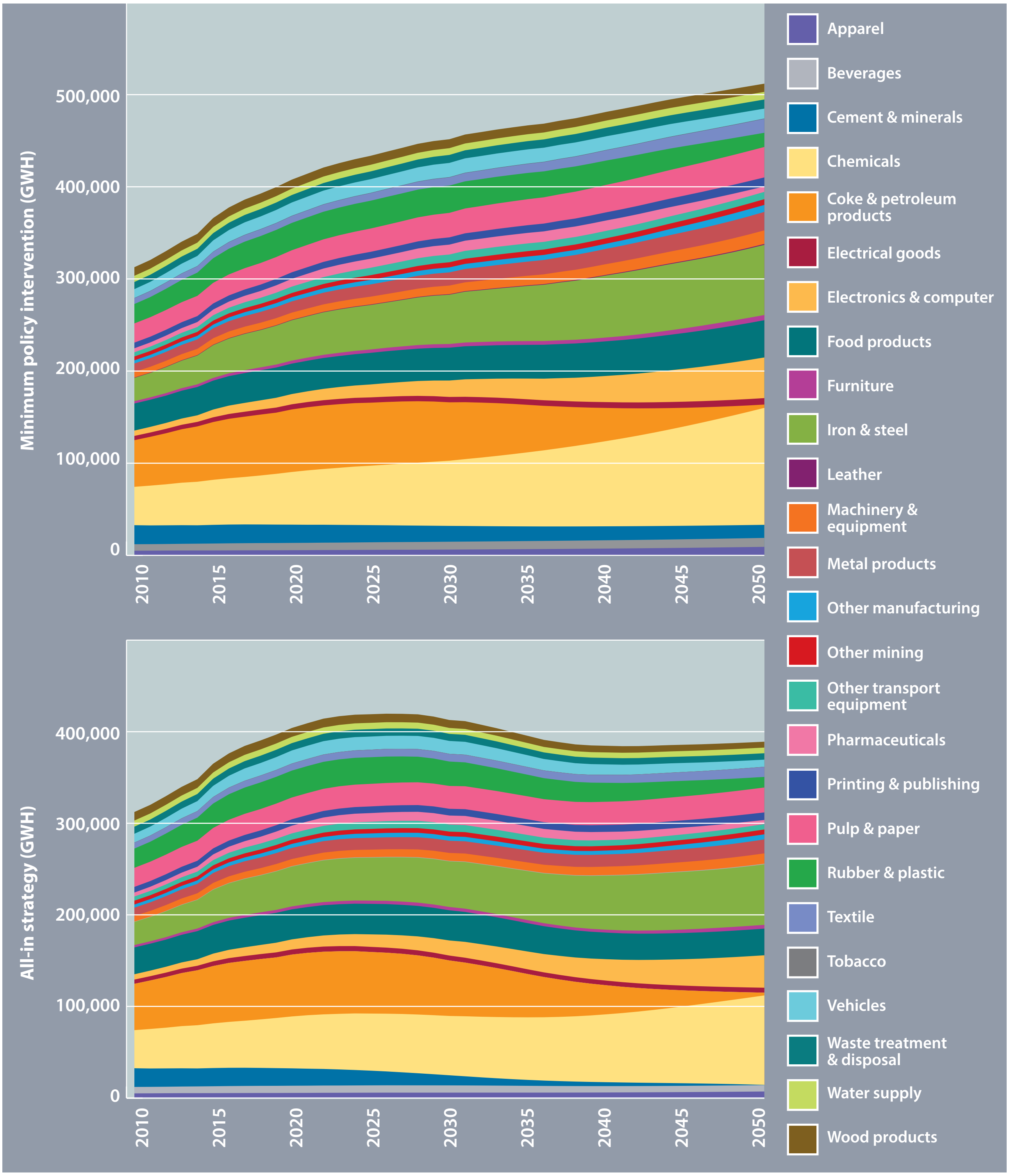
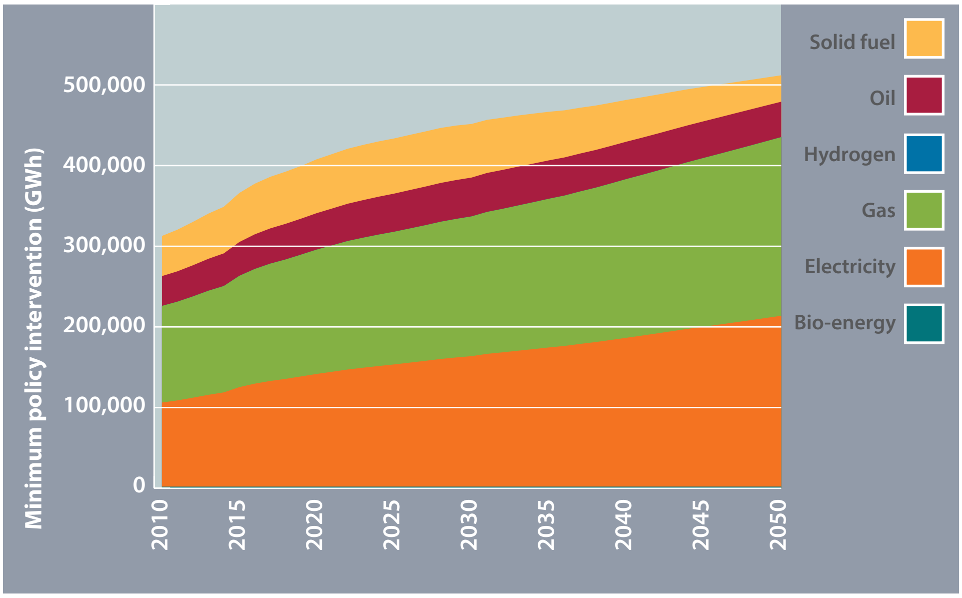
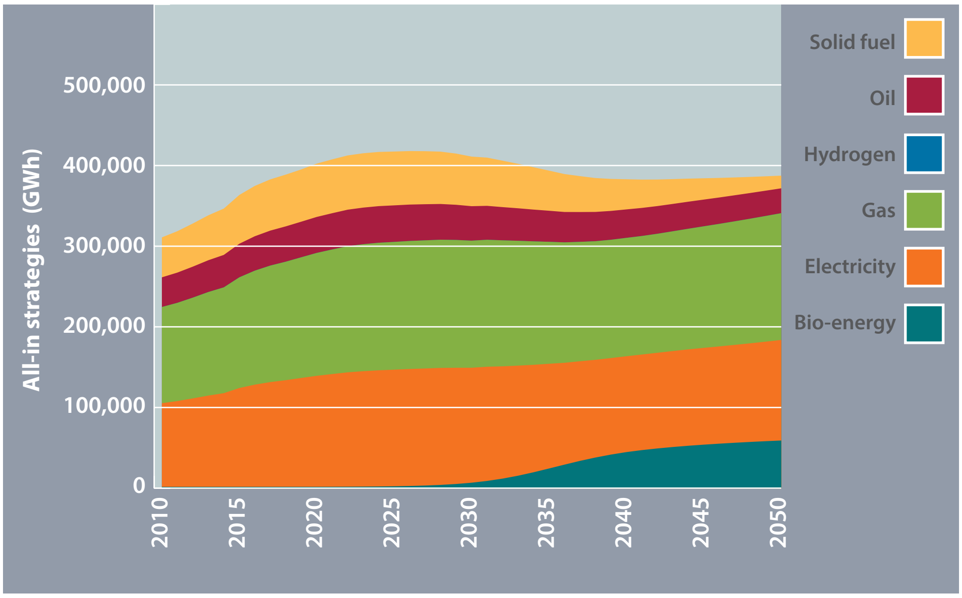


Figure 15 below compares the difference in energy consumption disaggregated by fuel resulting from the Minimum Policy Intervention (MPI) strategy versus the All-in strategy. The All-in strategy shows gas and electricity consumption still dominating, but with a noticeable penetration of bio-energy taken up from 2030 resulting in around 12% of total final energy demand by 2050.

Figure 15. UK industrial energy consumption by fuel under a high GDP growth scenario (2010 – 2050): A) Minimum Policy Intervention and B) All-in strategies.





The model also generates regional demand values making it possible to investigate changes by end use and regions. Figure 16 shows fuel demand for the All-in strategy in 2050 across 12 different regions. For a high investment strategy we can therefore compare the energy reduction opportunities between regions over time allowing us to track energy demand patterns between regions under a variety of future scenario assumptions. For this particular strategy we can see the low range in Northern Ireland at 10 TWh compared to a high of just over 40 TWh in the North West disaggregated by fuel type.

Figure 16. Final energy demand per fuel per region in 2050 assuming a high investment strategy (All–in) and a high GDP scenario.

41.3 KEY INSIGHTS

- Any GDP growth would lead to higher energy consumption in the absence of simultaneous energy intensity improvement. This supports the case for de-materialisation and re-use in industries to decouple industrial energy use and economic growth;
- Using an All-in strategy can save ~20% final energy consumption by 2050 when compared with a Minimum Policy Intervention strategy;
- Additional analyses can give more fine grained results at the technology level for example, despite a high relative reduction potential, sectoral electricity reductions from efficient motors, lighting, refrigeration and compressed air have been found to be insignificant relative to other measures. For CO2 reduction, there are greater opportunities in fuel switching than in energy efficiency, particularly in combined heat and power (CHP), as evident from a local biomass strategy (with large scale penetration of biomass CHP).

4.1.4 LIMITATIONS AND NEXT STEPS

- GVA inputs directly influences model results, particularly at regional and sub-sectoral levels. This captures the strong economy-industrial demand relationship and demonstrates the importance of assessing industrial demand pathways under a range of GDP scenarios;
- The current industry model will gather additional data for 3 other energy intensive sectors and develop and rerun the current strategies. Implementation of additional measures in chemicals, and pulp and paper is expected to capture opportunities in drying and separation, and high temperature end-use processes;
- Next steps include the development of a domestic energy demand model which will provide demand data for the energy supply team. Once this is developed we will be able to simulate peak grid demand and test strategies that focus on demand shifting. This step will also fully integrate the supply and demand models.

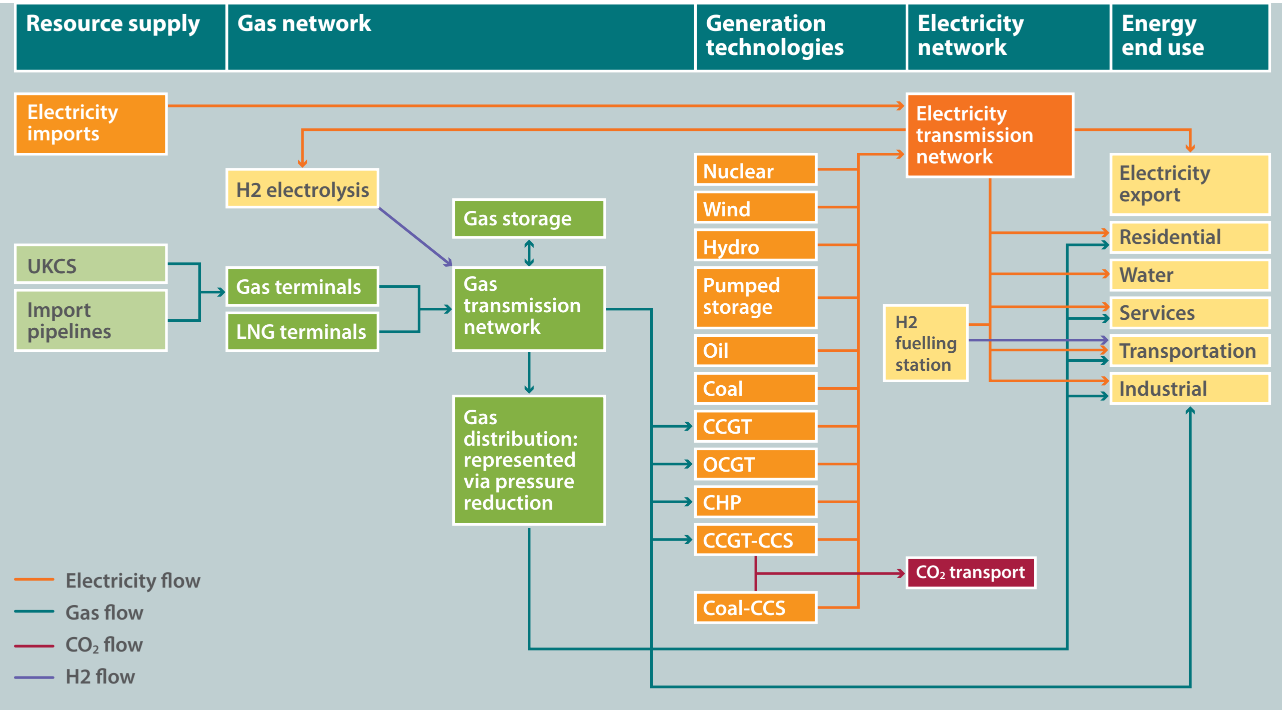
4.2 ENERGY SUPPLY

4.2.1 APPROACH

Energy supply implements the same set of strategies as energy demand ensuring consistency in scenario and strategy assumptions. For energy supply, strategies are modelled in 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 flow diagram of the CGEN+ model is shown in Figure 17. Different parts of the infrastructure are arranged into distinct categories, describing energy supply, energy transportation (gas and electricity networks), generation technologies, and energy end use.

Figure 17. Flow diagram considered in Combined Gas and Electricity model (CGEN+).



The diagram shows the CGEN+ model includes resource supply (UK Continental Shelf, imports, etc.) which includes bounds on the availability of primary energy supplies (gas, coal, oil etc.) and electricity imports. The gas network is modelled in detail to capture the dynamic nature of gas flows. The model performs DC load flow analysis for the electricity network. CGEN+ also includes an embedded generation expansion module that calculates optimal investment decisions. Generation technologies are described by a number of characteristics such as capital and operating costs, life time, maximum power capacity and thermal efficiencies. Energy demand is split into residential, industrial, transportation, services and water sector.

4.2.2 RESULTS

Figure 18 shows the results of power generation capacity when implementing the A) Minimum Policy Intervention (MPI) strategy and 3 variants of the Central electric/flexible consumer strategy including B) High nuclear, C) High CCS, and D) High offshore. The central electric strategy assumes high investment into low carbon electricity generation coupled with new demands for electricity in heating (heat pumps) and transport (electric vehicles) which are used to balance supply and demand. Overall, the electricity supply sector is assumed to change quickly with large and rapid investment into major low carbon power generation technology, with continued dominance of large companies. Within this strategy there are 3 variants that focus on CCS, offshore or nuclear uptake. See Appendix 1 for strategy narratives.

Figure 18. Power generation capacity when implementing the A) Minimum Policy Intervention (MPI) strategy and 3 variants of the Central electric/ flexible consumer strategy including B) High nuclear, C) High CCS, and D) High offshore (2010 – 2050).

The energy supply model allows us to compare technological uptake for a specific strategy. For example, in the MPI strategy CCGT capacity increases from under 30 GW in 2010 to 47 GW accounting for nearly 60% of total capacity in 2050. When comparing across the two strategies and associated variants we can see that the only option that significantly alters final capacity requirements is pursuing the High Offshore variant, which requires an almost doubling of generation capacity from 80 GW in 2010 to nearly 150 GW in 2050. This is due to low capacity factors for offshore power generation technologies.

Figure 19 below shows the performance between strategies in terms of electricity generation carbon emissions. The low investment MPI strategy sees an increase of carbon emissions of around 20% by 2050. The CCS strategy reduces carbon emissions the most around 95% followed by nuclear at 90%, and offshore generation achieves reductions of 60% over the same period.

Figure 19. Carbon emissions when implementing the A) Minimum Policy Intervention (MPI) strategy and 3 variants of the Central electric/flexible consumer strategy including B) Nuclear, C) CCS, and D) Offshore (2010 – 2050).

There are also important differences in total cumulative investment costs associated with each strategy. Assuming a 10% discount rate from a base year of 2010 the MPI strategy cost is ~£330 bn over the period 2010 – 2060, nuclear is ~£356 bn, CCS is ~£412 bn and offshore ~£713 bn which is a difference of £383 bn between the lowest and highest investment strategy. These costs are disaggregated by strategy in Figure 20.

When disaggregating the cumulative costs over time we can gain insight into the operational costs associated with different levels of technological uptake across different strategies. For instance, the MPI strategy sees lower electricity operational costs (compared with the other strategies) due to use of efficient CCGTs and uptake of new coal plants with low fixed costs, whereas nuclear uptake would see higher electricity operational costs due to high capital and fixed costs associated with new nuclear plants, and finally, the operational costs associated with offshore technologies would be the most high attributed to very high capital and on-going fixed costs. The key point here is that by modelling the different strategies we can gain insight into both system level performance such as carbon emissions, along with sectoral level detail such as operational costs associated with different levels of technological uptake.

4.2.3 KEY INSIGHTS

- There can be a large difference in cumulative investment costs even with a single strategy i.e. Central electric/flexible consumer strategy;
- There can also be large differences in system level performance metrics such as carbon emissions as a consequence of what strategy is taken. Between the two strategies including 3 variants the difference was as much as a 20% rise in carbon emissions for the MPI strategy versus nearly complete decarbonisation of the grid with CCS by 2050.

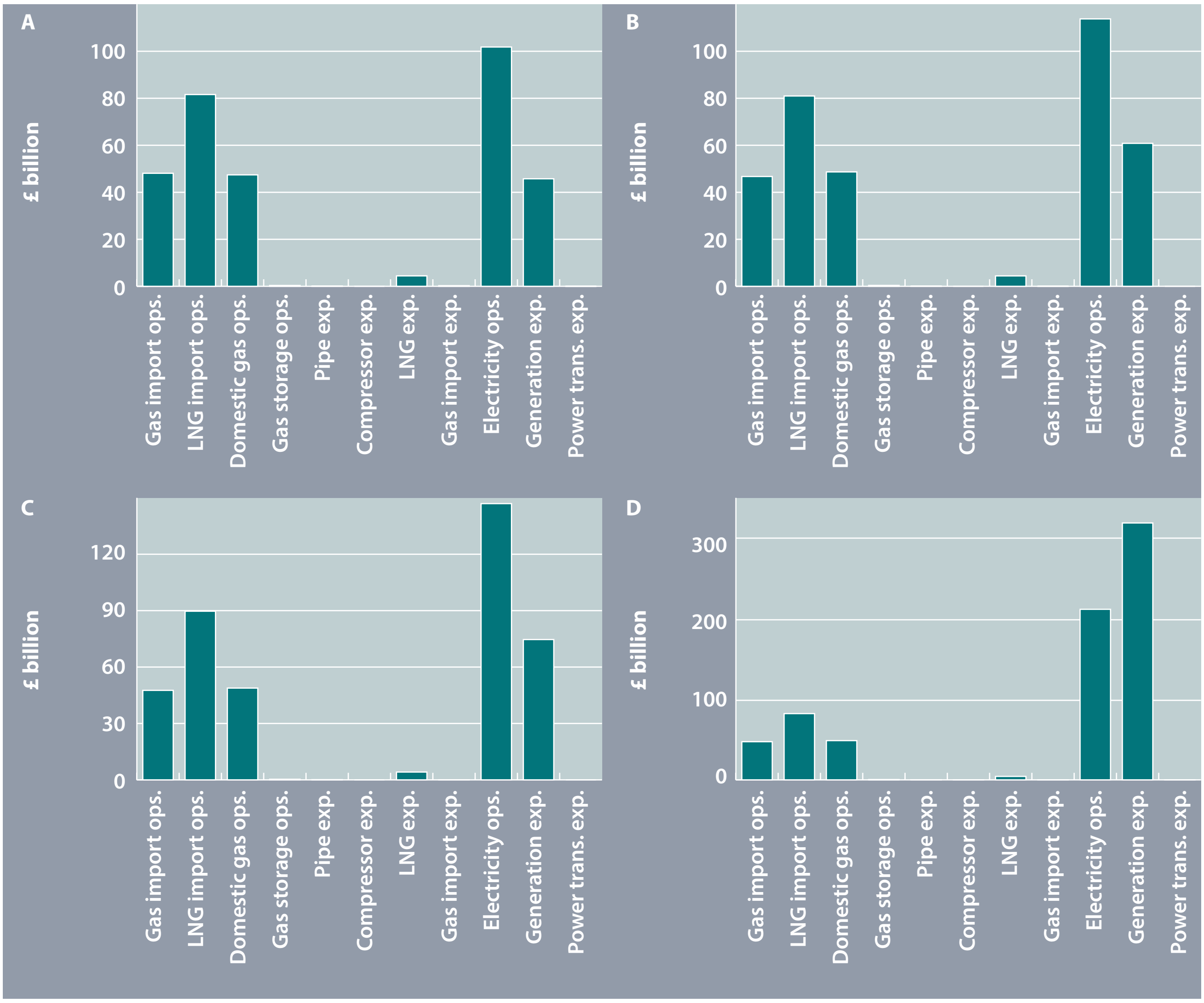


Figure 20. Cumulative costs over 2010 – 2060 when implementing the A) Minimum Policy Intervention (MPI) strategy and 3 variants of the Central electric/flexible consumer strategy including B) Nuclear C) Carbon Capture and Storage, and D) Offshore.

4.2.4 LIMITATIONS AND NEXT STEPS

- Currently, the energy supply outputs are based on 3 fuel price scenarios. Although there is some indication that energy supply may not be highly sensitive to fuel price, there is a possibility to test this assumption by exploring a wider range of alternative fuel prices as inputs in the next round of modelling runs;
- Annual electricity demand in 2010 is 328 TWh, it was assumed that this linearly increases to 342 TWh by 2050. This is currently a modelling assumption but will ultimately be provided by the energy demand team in the next round of model iteration.

4.3 TRANSPORT

4.3.1 APPROACH

There are currently 7 strategies that we can implement in the transport sector targeting a range of demand and supply side measures summarized in Table 3.

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.

The strategies are implemented in the NISMOD Transport Model, which is a strategic model that can assess the transport demand-capacity balance across Great Britain, with results disaggregated to the local authority level. It is able to rapidly identify key zones and links where demand-capacity mismatches are likely to arise, allowing more spatially-detailed models to then identify solutions to these mismatches. The Transport CDAM models capacity and demand 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 elasticity's 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, 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. Model settings can be specified via a Windows-based interface.

To generate these pilot results the transport model (along with all other sector models) takes the following economic and demographic input data summarized as follows:

1. Scenario D from demographics (the highest scenario) together with scenario 1D_1H_1L from economics (D demographics + high growth + low energy costs).
2. Scenario A from demographics (medium scenario) together with scenario 1A_1C_1C from economics (A demographics + central growth + central energy costs).
3. Scenario F from demographics (the lowest scenario) together with scenario 1F_1L_1H from economics (F demographics + low growth + high energy costs).

4.3.2 RESULTS

The first set of results is for strategy TR0 – Decline and Decay, which is effectively a do nothing strategy. This assumes that there will be no technological innovation and no improvement in vehicle performance. This strategy is therefore used as a baseline in which to compare other strategies that include technological progress and different levels of policy intervention.

Figure 21 shows total aggregated interzonal traffic for all three scenario inputs, showing that with this transport strategy strong growth is predicted under all three scenarios. Although it should be noted that this might potentially be affected by changes in energy costs.

Figure 21. Total aggregated traffic from interzonal road model for strategy TR0 (2010 – 2100).

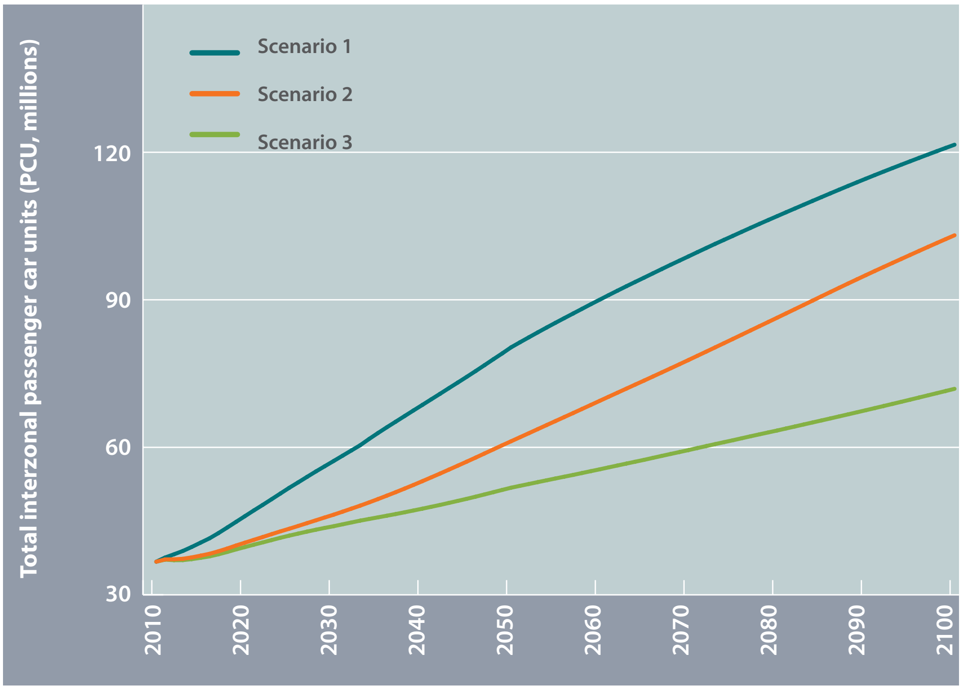


Figure 22 shows the growth in interzonal traffic for one flow in particular – Flow 169 linking Greater London and Surrey, with traffic disaggregated by road type. This shows both the differing rates of traffic growth produced by the three scenarios, and also the impact of increasing congestion levels which act to dampen traffic growth over time.

Figure 22. Traffic on Flow 169 with strategy TR0 disaggregated by road type (2010 – 2100).

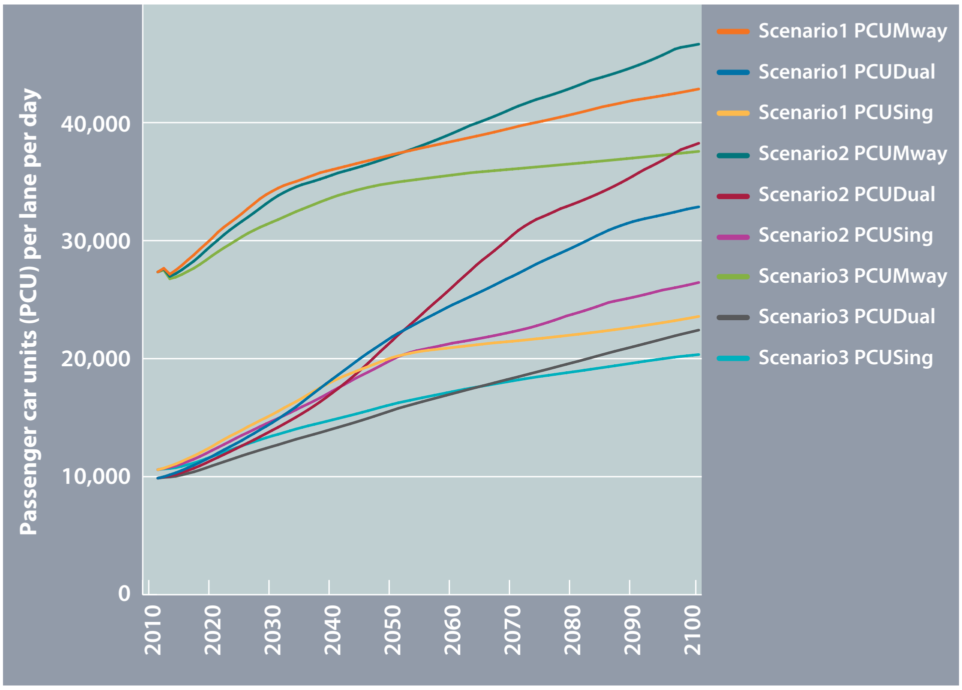


Figure 23 shows aggregated annual vehicle km and speeds from the intrazonal zone model. Unlike the interzonal model, this model has no binding capacity constraint, which allows exponential growth curves to be generated. Enormous growth in traffic is predicted by scenario 1, with even scenario 3 predicting that traffic will more than double over the study period. This figure does illustrate that there are very large differences in the forecasts produced under the three scenarios, with these differences growing over time. It also shows that average speeds would decline sharply as traffic grows, as a result of increasing congestion levels.

Figure 23. Total annual vehicle kilometres (Vkm) and speeds from intrazonal road model with strategy TR0 (2010 – 2100).

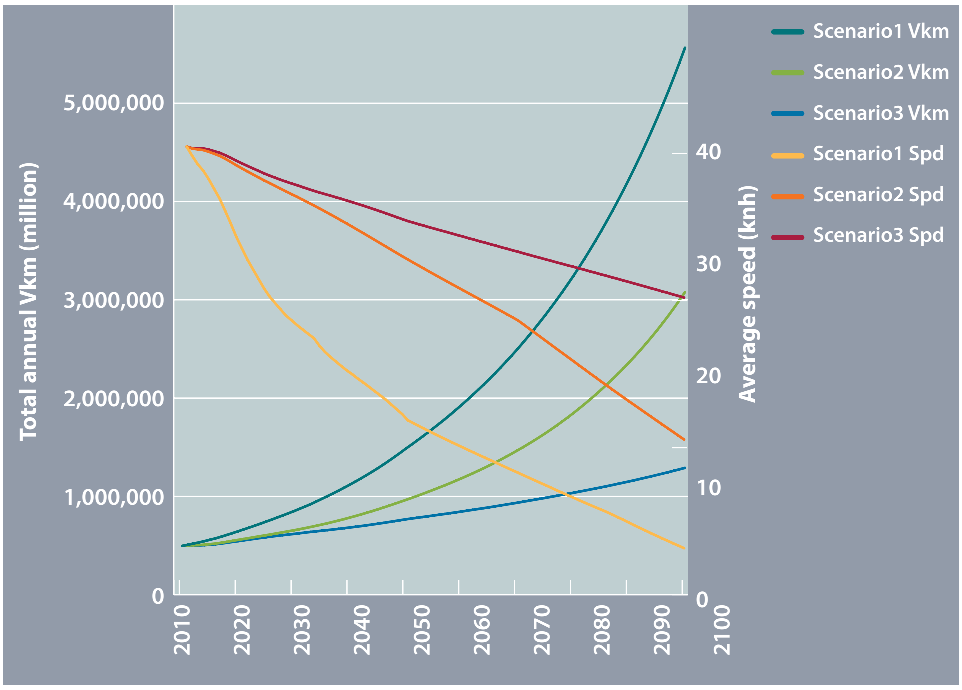
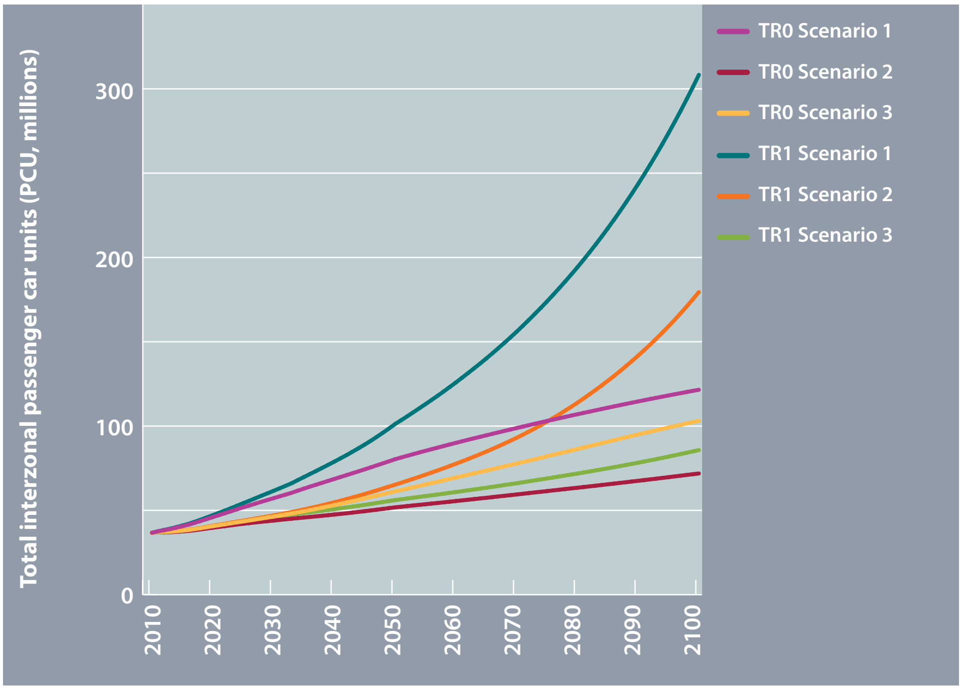


Figure 24 compares strategies TR0 and TR1 – Predict and Provide, which is intended to represent a future where demand modelling drives infrastructure construction, with large scale road building and widening programmes, airport and seaport expansion, and construction of additional railway lines. In order to model this strategy, additional functionality was added to the model to give the option for it to automatically build additional infrastructure capacity when a given level of capacity utilisation is reached for a particular link or node. This option is only switched on for Strategy TR1 with the critical capacity utilisation level set at 90%.

Figure 24. Total aggregated traffic from interzonal road model for strategy TR0 and TR1 (2010 – 2100).



We can see the significant difference between strategies when accounting for the full variation between scenarios where the potential difference between the highest (TR1 Scenario 1) and lowest is (TR0 Scenario 3) strategy is 300% in total aggregated traffic in 2100. This implies a massive difference in infrastructure performance and potential investment over the long term.

4.3.3 KEY INSIGHTS

- Continuing current trends in transport will result in a more than doubling of traffic even when assuming conservative economic and population scenario inputs. This is coupled with a corresponding decrease in average vehicle speeds due to growing congestion with important implications for health, safety and environmental emissions;
- Additional analysis indicates that rail traffic also grows much faster under Scenarios 1 and 2 than under Scenario 3, and that capacity utilisation and the level of delays increase accordingly;
- The pilot results indicate there can be a massive difference between strategies taken in transport. When comparing across all the economic and population scenarios along with 2 strategies (TR0 and TR1) there can be up to a 75% difference in total aggregated traffic by 2100. What this implies is at least one possible future that sees massive expansion of existing infrastructure (road, air, sea) along with additional construction of railway lines.

4.3.4 LIMITATIONS AND NEXT STEPS

- It is expected that the transport sector will be relatively more sensitive to fuel price scenarios compared to other sectors. It is possible to explore a wider range of fuel price scenarios in the next round of modelling runs, as well as modelling the full set of strategies under different fuel price assumptions;
- While other modes have been modelled at this step we have focused on presenting outputs for road transport. Next steps will focus on modelling the full set of strategies and providing outputs for all remaining modes including rail, ports, and airports.

4.4 WATER SUPPLY

4.4.1 APPROACH

The water sector consists of 9 strategies for water supply and 4 strategies for wastewater summarized in Tables 4 and 5. We currently report back pilot results for water supply only.

Table 4. Water supply strategies

	Strategy name	Demand change	Structural change	Capacity/Supply change
WR0	Current trends	WD0 – No change	WS0 – No change	WC0 – No change
WR1	Local resilience	WD2 – Demand management	WS0 – No change	WC9 – Desal. + effluent recycling
WR2	Closed loops	WD0 – No change	WS0 – No change	WC6 – Effluent recycling
WR3	Local integration	WD0 – No change	WS2 – Local integration	WC0 – No change
WR4	National integration	WD0 – No change	WS3 – National integration	WC0 – No change
WR5	Regional conservation	WD3 – Demand management	WS0 – No change	WC2 – Increased conservation
WR6	National conservation	WD2 – Demand decrease	WS3 – National integration	WC6 – Effluent recycling
WR7	Local crisis	WD1 – Demand increase	WS0 – No change	WC11 – All technologies + conservation
WR8	Uncontrolled demand	WD1 – Demand increase	WS1 – Targeted connectivity	WC12 – All technologies + aggr. conservation

Table 5. Waste water strategies

	Strategy name	Demand change	Structural change	Capacity/Supply change
WW0	Current trends	WWD0 – No change	WWS0 – No change	WWC0 – No change
WW1	Low environmental aspirations	WWD1 – Increase in volumetric demand	WWS1 – Increase volumetric capacity	WWC2 – Decrease in serviceability
WW2	Retrofit technologies within existing network	WWD0 –No change	WWS0 – No change	WWC3 – Change technology mix
WW3	Replace WWTW with new technologies	WWD2 – Decrease in volumetric demand	WWS3 – More decentralised	WWC3 – Change technology mix

See appendix 1 for strategy narratives.

The ITRC model of water supply infrastructure is a discrete-time 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.

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 rate, 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.

4.4.2 RESULTS

We currently present pilot results for Strategy WR3 – Local Integration, which assumes external pressures prohibit abstraction from the water environment. Thus, water service providers maximise the integration of strategic resources across their operational areas by enhancing the connectivity between regional water supply infrastructure networks. Prevailing water management practices persist, and per capita demand does not diverge greatly (if at all) from historical trends. For the current results capital costs of this integration are not considered at this time. The transmission capacities of distribution networks are unconstrained, facilitating total and unmitigated allocation of water between connected networks. The water model uses the same 3 sets of economic and demographic scenarios as input data used for all other sectors summarized in Section 4.3.1.

Pilot results indicate that the total demand for water, aggregated nationally is dependent on population size and reflects the growth trend in population (Scenarios 1 – high, 2 – central, 3 – low). Figure 25 shows the impact of constrained water supply on the volume available for allocation over 100 years. There is around a 50% decrease in the quantity of water available to meet growing demand across each scenario. Small differences in the quantity of water available to meet demand between scenarios reflect dependence between the capacities of networks to recharge, and the demand for water, implying further investment into network infrastructure capacity.

Figure 25. The quantity of water allocated to meet demand across 3 scenarios (2010 – 2100).

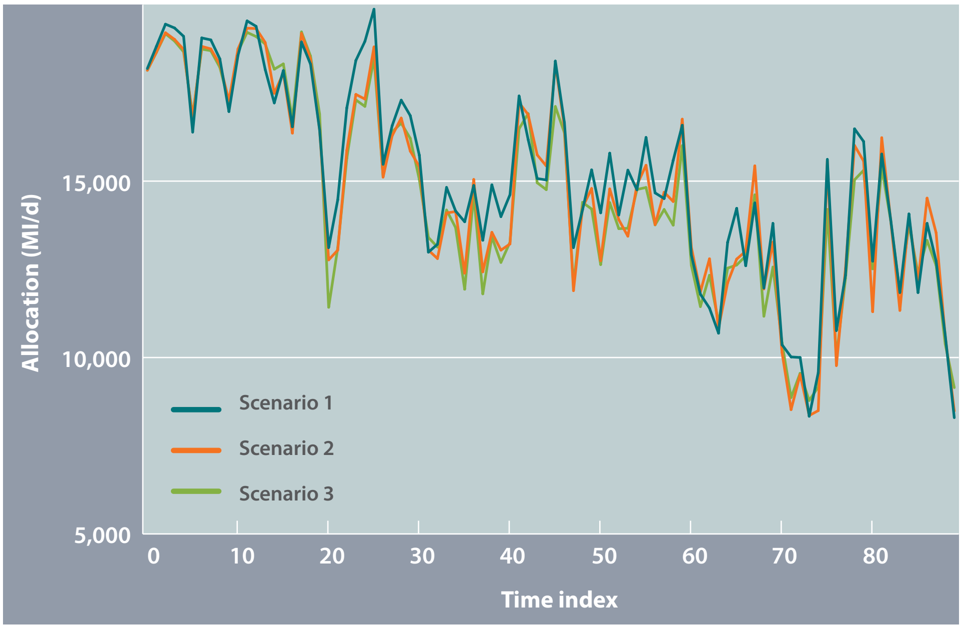
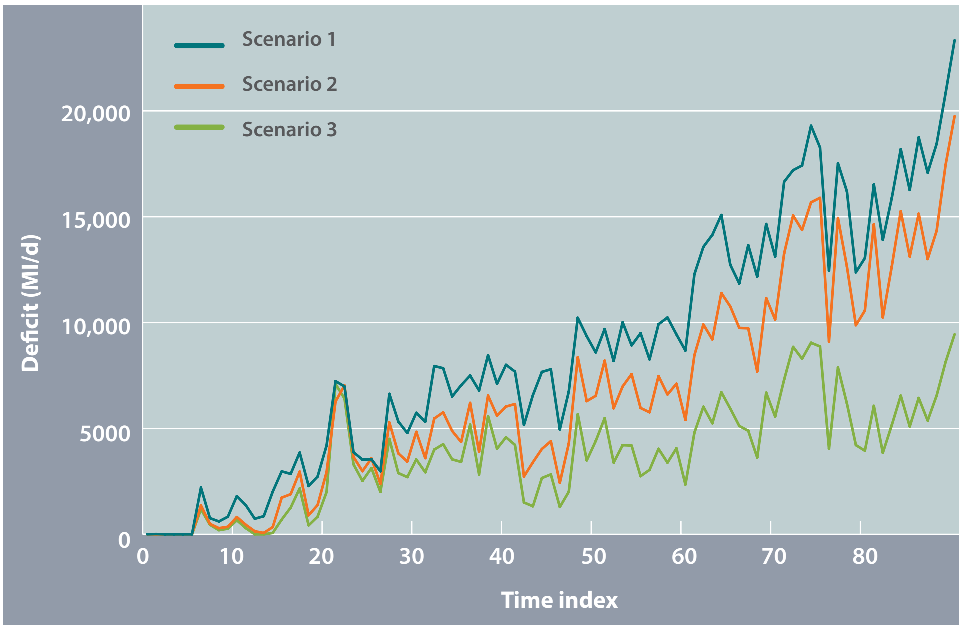


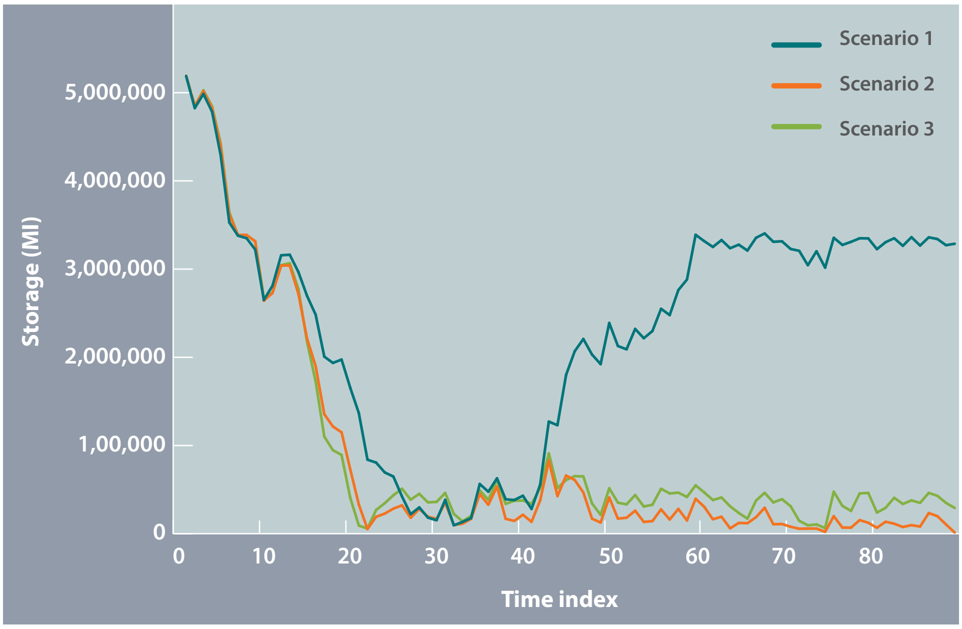
Figure 26 shows the deficit in the balance between the demand for water and the quantity of water available to meet that demand. Most water supply networks enter a state of deficit early in the study period, as increasing demand exhausts reservoir storage. Periods of recharge around 2050 and 2080 see decreases in the severity of the deficit; however, these periods are not of sufficient length to fully mitigate the shortage of water.

Figure 26. Deficit in water supply across 3 scenarios (2010 – 2100).



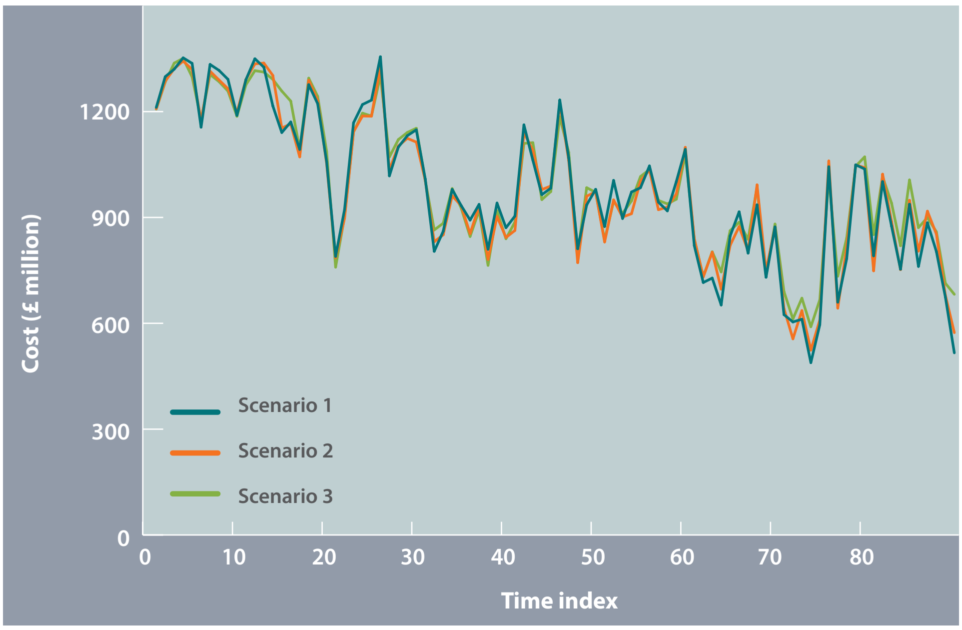
The quantity of water stored in reservoirs explains some of spatial distribution of the deficit shown in Figure 27. Although storage diminishes rapidly under all scenarios, it recovers substantially under the supposition of high growth in the demand for water; however, this recovery occurs almost entirely in Scotland. With no means of conveying water from Scotland to the rest of the UK under this strategy, it is unavailable for allocation outside of Scotland.

Figure 27. Differential levels of water storage across 3 scenarios (2010 – 2100).



Other pilot results show the direct cost (Figure 28), power cost, and the greenhouse gas emissions arising from water supply. As each quantity is proportional to the quantity of water allocated to meet demand, with some departures attributable to the cost of fuel, these variables generally follow the trend of Figure 25. All quantities decrease over time, as constraints on the quantity of water abstracted from sources of water throttle the quantity allocated to meet demand. In this context, it is relevant to note that the costs and rate of emissions arising from scenarios that feature low population growth can exceed those arising from scenarios that feature high population growth, as there is more water resource available for allocation under scenarios of low-demand.

Figure 28. Direct costs arising from water supply across 3 scenarios (2010 -2100).



4.4.3 KEY INSIGHTS

- Hydrological constraints define the performance of the water supply infrastructure network as much as infrastructure capacity constraints;
- A more realistic treatment of network transmission capacity will be necessary for long-range projection.

4.4.4 LIMITATIONS AND NEXT STEPS

- Pilot results are based on a reduced set of 11 water supply infrastructure networks, corresponding to the spatial extents of the major water supply infrastructure owners in the UK. In practice, there are over 100 recognised sub-regional water resource zones, each comprising a network, with some targeted connectivity between networks at the level of distribution post-treatment, as well as between water resources at the level of distribution pre-treatment. This neglects a considerable proportion of the population not served by the networks of the 11 major water supply infrastructure owners;
- In addition to the above, the model considers only demand directed at the public water supply infrastructure system. This neglects demand arising from other uses of water, such as agriculture, industry, and energy generation.
- Next steps include using a more representative sample of climate variables to calibrate and project network behaviour along with disaggregation of abstractions and reservoir storage within networks, and the attribution of hydrological variables from appropriate regimes. This will allow for improved spatial representation of networks and differential abstraction behaviour.

4.5 SOLID WASTE

4.5.1 APPROACH

The waste sector currently has 6 different strategies that can be implemented summarized in Table 6. These strategies are implemented by the Solid Waste Capacity-Demand Assessment Model (CDAM). The model assesses the solid waste demand and capacity balance at a government region scale. The solid waste CDAM 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. This is based on changes in regional population and GVA and energy costs. The solid waste model has used the same economic and demographic input data as the other sectors representing a high, low and central case population growth.

Table 6. Solid waste strategies

	Strategy name	Demand change	Structural change	Capacity/Supply change
WE0	Business as usual	SWD0 – partial decoupling	SWS0 – No change	SWC1 – Thermal treatment increase SWC2 – Bio treatment increase SWC3 – Increase in recycling
WE1	High tech	SWD2 – increase in arisings or SWD0 – partial decoupling	SWS0 – No change or SWS1 – National planning	SWC1 – Thermal treatment increase SWC2 – Bio treatment increase SWC3 – Increase in recycling
WE2	Closed loop, zero waste	SWD0 – partial decoupling or SWD1 – full decoupling	SWS1 – National planning and SWS2 – Taxation & targets	SWC3 – Increase in recycling
WE3	Deep green	SWD1 – full decoupling	SWS1 – National planning and SWS2 – Taxation & targets	SWC0 – No change SWC4- Increase in reuse/ recycling
WE4	Maximum energy	SWD0 – partial decoupling or SWD2 – increase in arisings	SWS0 – No change or SWS1 – National planning	SWC1 – Thermal treatment increase SWC2 – Bio treatment increase SWC5 – Reduction in recycling
WE5	National plan	SWD0 – partial decoupling or SWD1 – full decoupling	SWS1 – National planning and SWS2 – Taxation & targets	SWC1 – Thermal treatment increase SWC2 – Bio treatment increase SWC3 – Increase in recycling

See Appendix 1 for strategy narratives.

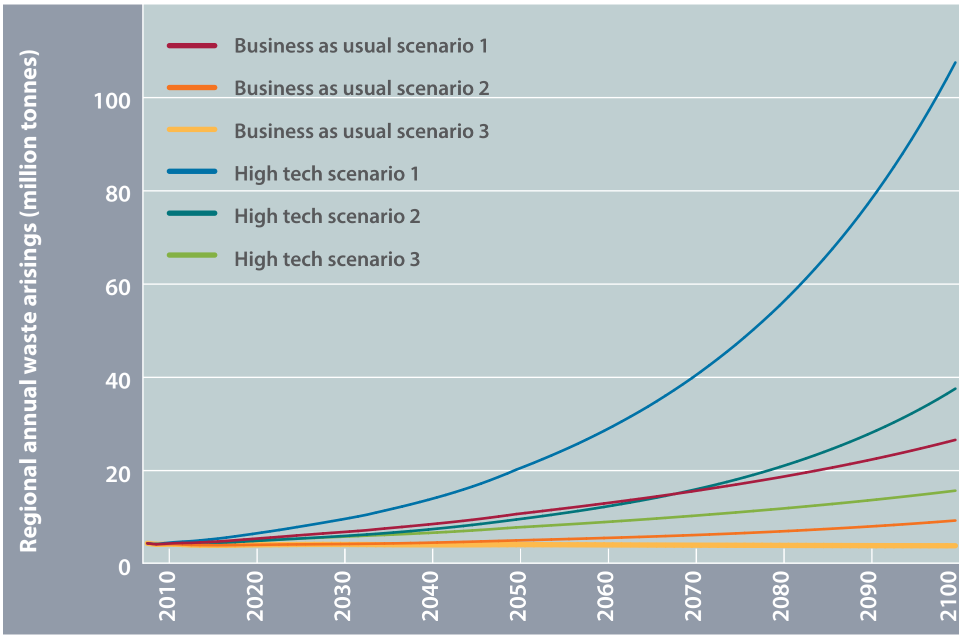
4.5.2 RESULTS

Two strategies have been examined: WE0 – Business as usual, and WE1 – High Tech. In both cases, recent trends of waste reduction are continued but at different rates. The Business as usual case assumes a 2% per annum reduction in per capita per GVA waste arisings, which as can be seen in Figure 28 will lead to an overall reduction in waste arisings in some of the scenarios. The High Tech strategy assumes a technological solution to the problem of waste arisings; this has the effect of disconnecting the public from their waste and results in a lower rate of waste reduction (0.5% p.a.) which is primarily due to reengineering of products and packaging rather than any behavioural change. It should be noted that the recent trends of household waste arisings show annual decreases of 5%, so these reductions are conservative.

The results for the South East region are shown below. Figure 29 shows the overall MSW arisings for the South East for each scenario and strategy. Figure 30 shows the amount of MSW which needs to be recycled or composted in order to meet current targets (40% by 2010; 45% by 2015; 50% by 2020) along with the current capacity in the South East (red line). It should be noted that while there appears to be significant excess capacity for the first few years, some of this is shared with the household waste-like component of commercial waste.

Figure 31 shows the residual waste remaining; it is assumed that the recycling and composting targets have been met but not exceeded (i.e. worst case scenario). The red line shows residual waste treatment capacity for the South East. It includes the current capacity as well as planned capacity which has received planning consent. The new capacity is added in the year in which it is likely to become operational. It should be noted that for population scenarios a-d; the population increase in the South East of England is in each case highest or equal highest in Great Britain, so whilst the results presented here are for the region, they are typical of Great Britain as a whole, they are also the most extreme. The initial shortfall between residual treatment capacity and demand will be met primarily by landfill but also by some waste exports.

Figure 29. Municipal solid waste (MSW) arisings in the South East region for scenarios 1, 2 & 3 (2010 – 2100).



4.5.3 KEY INSIGHTS

- In the Business as usual strategy, waste arisings will exceed the capacity for recycling and composting by 2035, whereas in the High Tech strategy in scenario 1, because of increased waste production, additional recycling and composting capacity will be needed by 2025 (Figure 30);
- For all but the highest growth scenario (scenario 1), current residual waste treatment capacity in the South East region is at least sufficient from 2017 until 2035. For scenarios 2 and 3, and the Business as usual strategy, the current and consented capacity is sufficient until beyond 2070 (Figure 31);
- A continuation of the current trends of reductions in MSW would see an overall reduction of waste amounts regardless of the growth scenario.

Figure 30. Municipal solid waste (MSW) recycling and composting requirements for the South East region for scenarios 1, 2 & 3 (2010 – 2100).

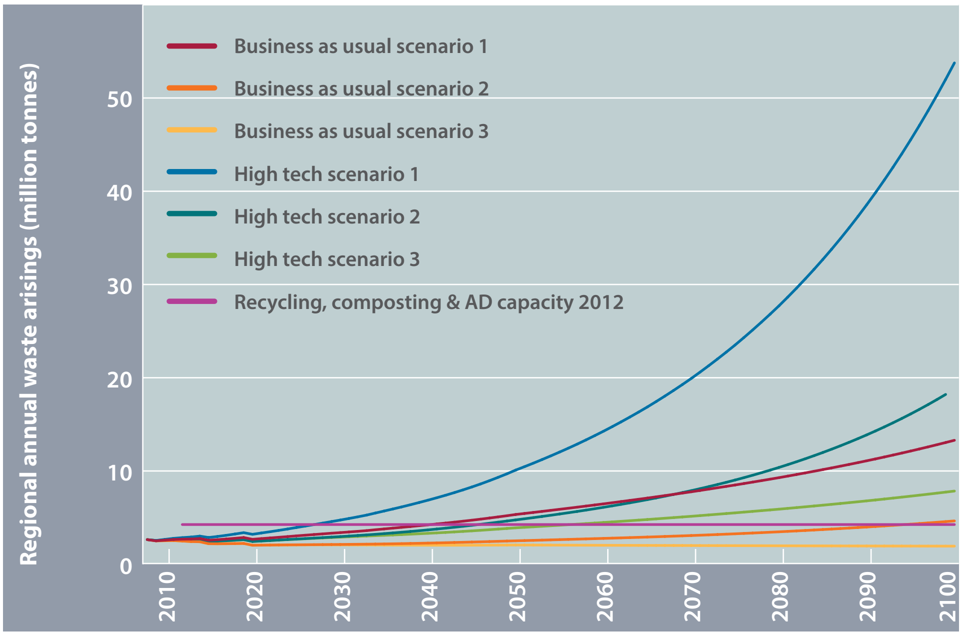
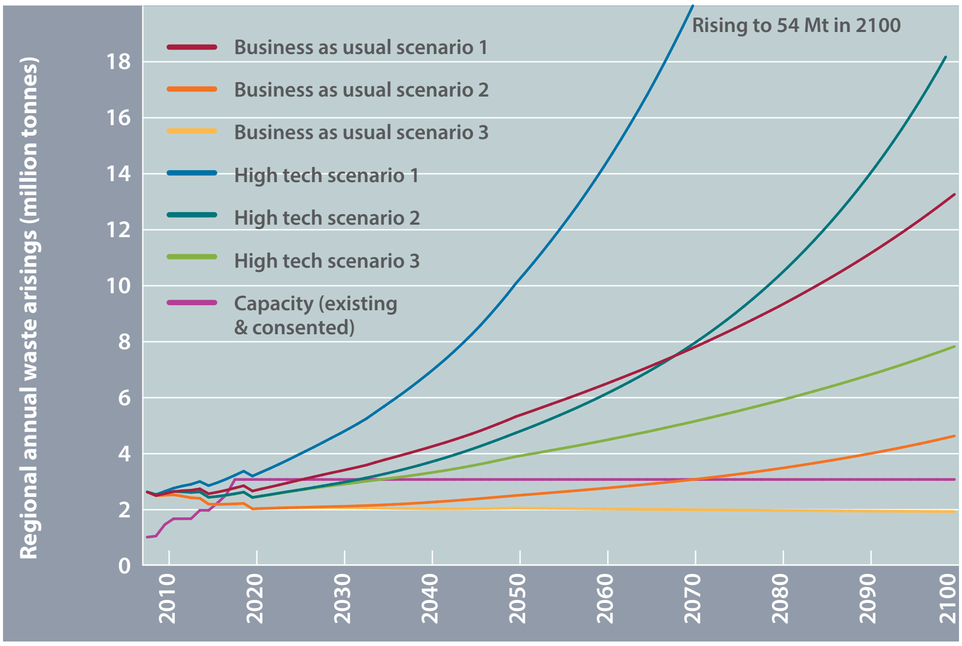


Figure 31. Municipal solid waste (MSW) residual arisings and current and consented treatment capacity for the South East region for scenarios 1, 2 & 3 (2010 – 2100).



4.5.4 LIMITATIONS AND NEXT STEPS

- The spatial disaggregation is at a regional level rather local authority level which is the level at which household waste disposal decisions are currently made;
- Poor data for commercial and industrial (C&I), and construction and demolition (C&D) waste make it very difficult to get a handle on historic waste arisings and hence likely future waste levels;
- Next steps involve altering the model to optimise both treatment type and transportation. The current optimisation procedure needs to be simplified without losing important detail;
- All remaining strategies will be modelled in the next round of iteration combined with updated data from the economic and demographic scenarios.

5 Cross sector messages and next steps

5.1 PERFORMANCE OF ALTERNATIVE STRATEGIES

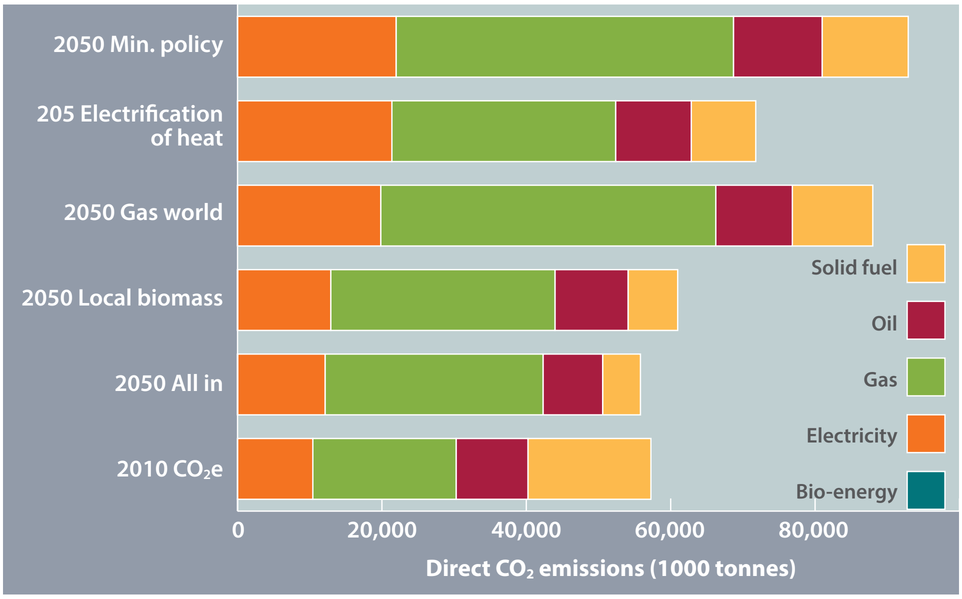
An important cross sector message arising from the pilot results is that there exists a range of possible alternative strategies for each sector, and they can have very different outcomes. The potential difference in long term infrastructure performance between high and low investment strategies can be seen even with the limited number of strategies that have been modelled. For example, in the energy sector an All-in strategy, which focuses on deploying multiple technologies and demand management measures, could result in a 23% decrease in final industrial energy consumption by 2050 as compared to a low investment MPI strategy. And for energy supply, a low investment MPI strategy sees an increase of carbon emissions of around 20% by 2050; whereas, the CCS strategy reduces carbon emissions the most at 95% followed by nuclear at 90%, and offshore generation achieves 60% reductions over the same period.

There are also important differences in total cumulative investment costs associated with each strategy. The MPI strategy cost is around £330 bn over the period 2010 – 2060, whereas nuclear is £356 bn, CCS is £412 bn and offshore £713 bn. This means there is a substantial difference of £383 bn between the lowest and highest investment strategy available. When disaggregating the cumulative costs over time we can also gain insight into the operational costs associated with different levels of technological uptake across different strategies. For instance, the MPI strategy sees lower electricity operational costs (compared with the other strategies) due to use of efficient CCGTs and uptake of new coal plants with low fixed costs, whereas nuclear uptake would see higher electricity operational costs due to higher capital and fixed costs associated with new nuclear build.

For the transport sector pilot results also imply a substantial difference between strategies taken. When comparing across all the economic and population scenarios along with 2 strategies where one assumes current trends (TR0) and another that assumes unconstrained growth (TR1) there can be up to a 75% difference in total aggregated traffic over the long term (2100). What this implies is at least one possible future seeing massive expansion of existing infrastructure, along with high levels of investment for additional capacity across all modes (road, rail, air, sea).

When comparing across alternative strategies, we can therefore see important differences in infrastructure performance. Figure 32 shows carbon emission in 2050 for 5 different energy demand strategies. The All-in and Local Biomass strategies result in 20% less CO2e emissions than Electrification of Heat, and 40% less than Minimum Policy Intervention. The key point here is that by modelling the different strategies we can gain insight into both system level performance such as total final energy demand, carbon emissions, as well as sectoral level detail such as, operational costs associated with different technologies, and levels of uptake over a long term planning horizon.

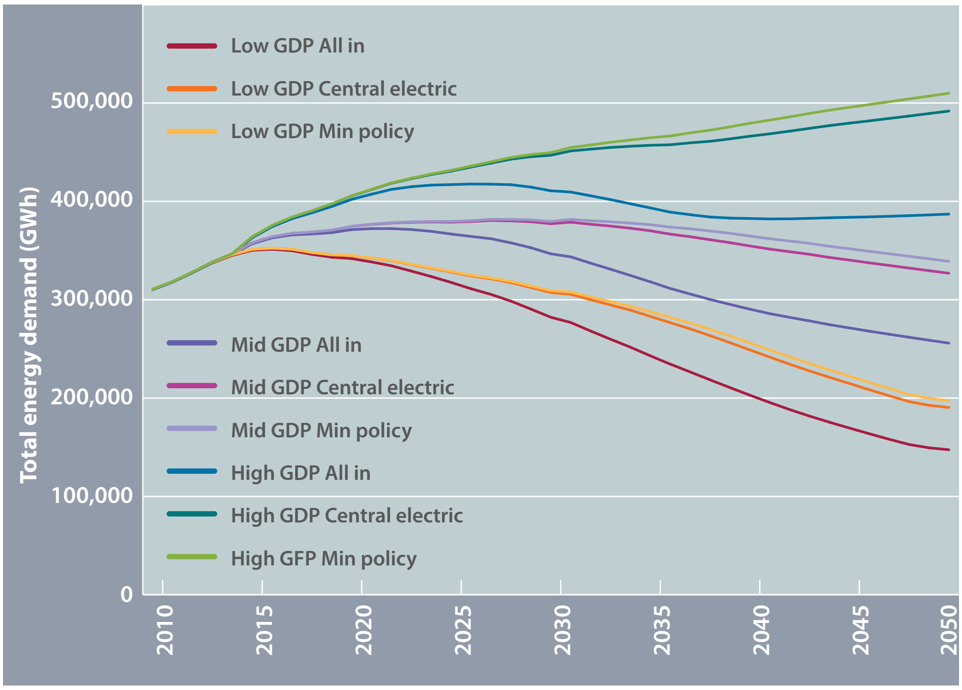
Figure 32. Direct CO2 equivalent emissions for all strategies in 2050 under a High GDP scenario. Notes: CO2e tonne assumes 100% grid electricity at 20% of 2009 Defra emission factors.



It is also important to recall that each sector strategy will be influenced by the economic and demographic assumptions that have been developed into future scenarios. For the economic scenarios alone there is a possible 72 future projections that can be developed with different impacts on the performance of sector level strategies. For example, total demand for water is closely linked to population trends where the costs and rate of emissions arising from low population growth scenarios can exceed those arising from high population growth scenarios, since there is more water resource available for allocation under scenarios of low-demand. As such, hydrological constraints can influence the performance of the water supply infrastructure network, as much as infrastructure capacity constraints. The impacts of scenario variation can also be seen in the solid waste sector at the regional level giving insight into capacity constraints and necessary investment strategies. For instance, for all but the highest growth scenario (scenario 1), current residual waste treatment capacity in the South East region is sufficient from 2020 until 2035. And for the central and low case assumptions, the current capacity is sufficient until beyond 2070.

When we therefore account for the influence of macro level demographic and economic scenarios combined with sector specific strategies, the space of alternative future outcomes opens up even more. This highlights the importance of investment decisions we make today, and how this will impact upon future infrastructure performance. For example, Figure 33 provides the results of 3 energy strategies combined with 3 GDP scenarios resulting in a low final energy demand in 2050 of 150 TWh compared to a high outcome of 500 TWh. We can also see the cumulative effects of our decisions such that the differences between strategy outcomes are even greater as we look further out in time. However, the range of possible strategy outcomes also implies that we may not be as locked in as we think. This should incentivise us to plan and invest into infrastructure provision over a far longer time horizon than what is conventionally done today.

Figure 33. UK Industrial energy demand evolution combining GDP economic scenarios and energy strategies (2010 – 2050).



5.2 DEMAND DRIVEN CHANGE

One of the emerging crosscutting themes arising from the pilot results is to further investigate how trends in population, demographics and economic signals might impact consumer behaviour and shape future demand for service provision. Across all of our current eight population scenarios GDP increases with a range of £2.7-3.7 trillion by 2050. This is coupled with higher population growth with 60 – 140 million people by 2050, and continued and rising dominance of the services industry, all of which leads to increased demand for infrastructure provision.

For example, alternative demographic projections tend to have the following effects: 1) a larger population tends to increase expenditure by households across the economy; 2) a larger population also increases the size of the workforce, permitting higher employment; a higher availability of labour may also curb wage growth; and, 3) a larger population will also raise demand for government goods and services, and therefore the necessary infrastructure to support such services.

Our current demographic scenarios primarily see the highest levels of population growth and urbanisation around London and the South-East of England. However, we can make different assumptions on demographics to show higher levels of population growth and associated urbanisation in the North West. For example, by adjusting our assumptions, Figure 34 shows more rapid population growth in the North West regions with negative net migration out of London by 2020, which might be explained by a desire to move out of London due to increasingly high population density.

Additionally, all economic scenarios show the consistent dominance of private services around the London area. But under a scenario that sees net migration out of London and increased urbanisation in the Northwest it is conceivable that private services might also shift to that region. It will therefore be important to consider all possible scenarios of migration, and demographic change that might lead to new demand trends away from the conventional focus on London and surrounding areas.

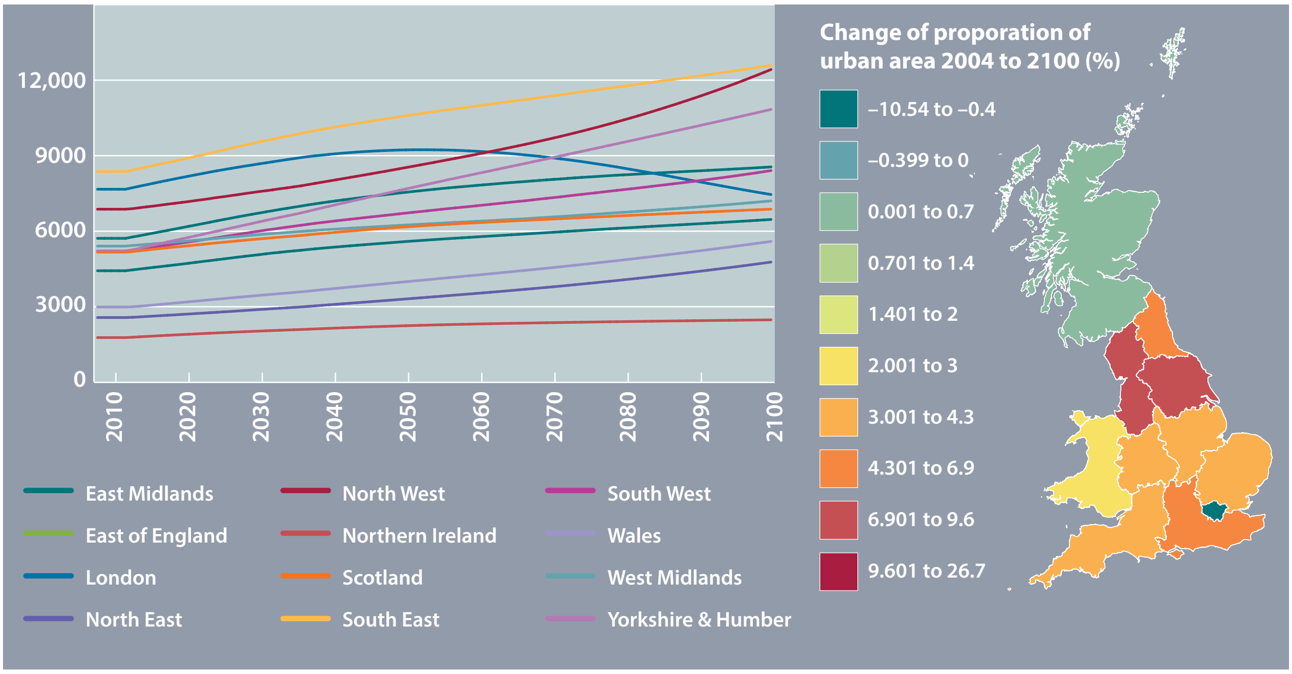


Figure 34. A (above left) Change of population for Government Office Regions (GORs) and B (above right) corresponding urbanisation map under a new demographic and population scenario (2004 – 2100).

The implication is that future investment will need to ensure adequate provision of infrastructure services to those regions with projected future growth. Depending on the infrastructure type, this may require the construction of new assets in these regions or, alternatively, an expansion of carrying/transmission capacity from other regions. The relative performance of alternative transition strategies for such provision is a key aim of the assessments carried out in the sector models. The important question here will be how to anticipate and plan for new infrastructure provision to meet unexpected regional shifts in consumer demand.

As previously noted, we have only modelled 3 out of a possible 72 economic scenarios. In the current scenarios we use relatively conservative fuel prices and assume real price remains constant after 2030 (although rising in nominal terms) in line with current DECC projections. Historically, lower fuel prices have been associated with higher economic growth and GDP, while high fuel prices have suppressed growth. It is conceivable that more extreme fuel prices will impact future infrastructure demand through price signals, particularly for example in the transport sector.

Aside from potentially unanticipated shifts in regional population growth, urbanisation and economic price signals, it is important to recall that new demand will also arise from technological change and progress. Various strategies across each sector currently embed assumptions on new demand arising from the uptake of smart meters and electric vehicles for example. This will increase interdependency between the energy and transport sectors. Future model runs will focus on how new interdependencies might impact future demand and the corresponding infrastructure performance of each sector.

It will be important to determine both the scale and timing necessary for infrastructure investment to meet growing demand. Assessing the different patterns of demand growth is central to the work of ITRC and is captured in our ability to model different macroeconomic and population drivers, and how these drivers might impact upon infrastructure provision for each sector.

5.3 ICT INTEGRATED SYSTEMS

Current trends indicate an increased uptake of information and communication technologies (ICT) across sectors. An impact of ICT is that it cuts across supply and demand and will therefore shape investment needs for capacity provision and potentially alter future demand trends. For example, there are particularly strong interdependencies between energy and transport with the EU and UK implementing policies to encourage investment into smart network architecture, and mass roll out of smart meters by 2020. It is believed that there is potential to increase overall system efficiency by better matching energy demand and supply through improved data monitoring and information feedback. For example, network operators will get more detailed information about supply and demand improving management of the system such as shifting demand to off-peak times. As a result, a smart network will be able to better accommodate mass penetration of intermittent renewables and electric vehicles. However, there are many unanswered questions surrounding the system wide impacts of mass uptake of ICT.

Some of our pilot results can capture the effects of ICT uptake. For instance, transport strategy (TR5) called 'Connected Grid', envisages a future where maximum possible use would be made of ICT to enhance the operation of transport systems, with a high and increasing level of embedded technology. This is represented in the model by progressively increasing the effective capacity of transport infrastructure, but also by reducing the GVA elasticity over time to reflect the increasing substitution of technological interaction for travel.

Figure 35 shows the aggregate interzonal motorway traffic predicted by the model using these three different strategies for comparison. This shows that the effective removal of any capacity constraint with Strategy TR1 leads to an exponential pattern of growth. Strategy TR5 generates greater traffic growth than TR0, with a much lower level of infrastructure construction (the model was allowed to build a maximum of two additional interzonal road lanes per year), but this growth does not take off in the same way as under Strategy TR1.

Figure 35. Aggregate interzonal motorway traffic in Scenario 2 with Strategies TR0, TR1 and TR5 (2010 -2100).

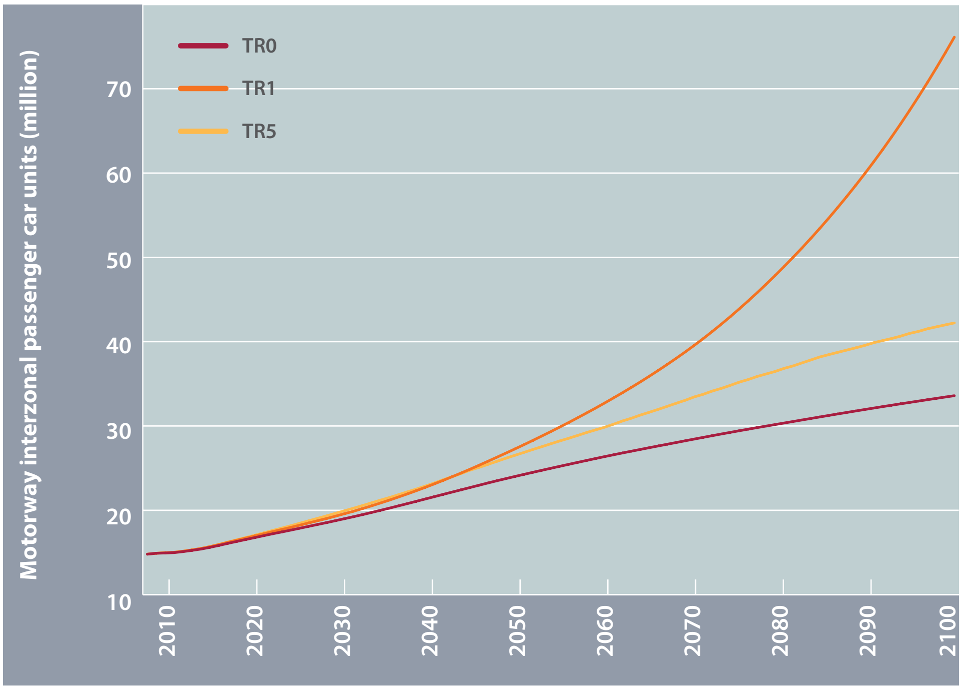
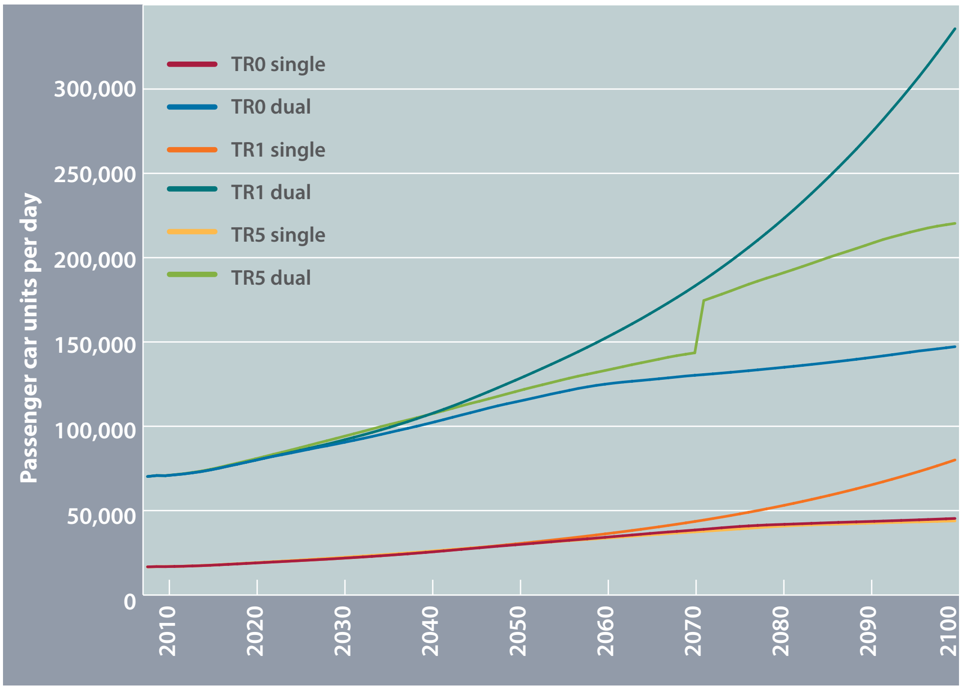


Figure 36 illustrates the effects of additional infrastructure construction on Flow 146. In Strategy TR1, additional dual carriageway capacity is constructed in 2045, 2061, 2074, 2083, 2090 and 2097, before the existing capacity is full, giving the smooth curve of traffic growth shown in the chart. In TR0 no additional capacity is constructed, meaning that traffic growth is suppressed, with the growth curve flattening out towards the end of the century. In Strategy TR5, in contrast, additional capacity is built in 2072, leading to a sudden step growth in traffic almost to TR1 levels, but continued congestion means that growth continues at a lower rate than in Strategy TR0. No additional infrastructure is constructed on single carriageway roads in either Strategy TR0 or TR5, and because technology is assumed to bring no capacity benefits to single carriageway roads in Strategy TR5 the growth curves for such roads are identical with these two strategies.

Figure 36. Passenger Car Units (PCU) per day on Flow 146 in scenario 2 with Strategies TR0, TR1 and TR5 (2010 – 2100).



The pilot model runs have so far focused on a limited number of strategies. But there are strategies within each sector that embed assumptions about increased uptake of ICT. The next round of model runs will draw this out more explicitly and consistently across each sector, and attempt to assess the system wide impacts of ICT. Future work will also assess how ICT might be a focal point to analyse interdependencies between each sector. One way forward is to assess the evidence base on ICT impacts upon each sector and re-parameterize the models to simulate efficiency improvements. However, a potential barrier might be the lack of evidence for ICT impacts upon other sectors. This will need to be further explored. The central point is that the ITRC recognizes the importance of ICT and will seek to better integrate this into our modelling capability.

6 References

Cabinet Office, 2010. Sector Resilience Plan for Critical Infrastructure 2010. London: Cabinet Office.

Department for Energy and Climate Change (DECC) fossil fuel-price assumptions from the most recent Updated Energy and Emissions Projections publication.

Hall, J.W., Henriques, J.J., Hickford, A.J. & Nicholls, R.J., eds., 2012. *A Fast Track Analysis of Strategies for Infrastructure Provision in Great Britain*: Technical Report. Oxford: Environmental Change Institute, University of Oxford.

HM Treasury & Infrastructure UK, 2011. National Infrastructure Plan 2011. London: The Stationery Office Limited.

Karlsson, M., Mayhew, L., Plumb, R. and Rickayzen, B. 2006) Future costs for long-term care: Cost projections for long-term care for older people in the United Kingdom. *Health Policy* **75**(2) 187–213

Mott MacDonald, 2010) UK Electricity Generation Costs Update.

National Grid, 2011). Gas Ten Year Statement.

National Grid, 2011) Electricity Seven Year Statement.

ONS, 2008). 2008-based National Population Projections. The Office for National Statistics.

7 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	**Central electric/flexible consumer**	There is a continued emphasis on strong climate policies with targets generally met. Concerns about energy security continue and are addressed primarily 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. Smart meters are rolled out and increasingly used in demand response programmes in all demand sectors. In particular, new demands for electricity in heating (heat pumps) and transport (electric vehicles) are used to balance supply and demand. The electricity supply sector changes quickly in line with current policy plans. 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

Energy headline strategies – narratives		
	Strategy name	**Example narrative**
EN1	*continued*	**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.
EN2	**Solar world**	There is a continued emphasis on strong climate policies with targets generally met. Concerns about energy security continue. Both are addressed by increasing amounts of local investment, in both demand reduction technologies and distributed solar PV. 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 energy issues as solar energy deployment becomes mainstream behaviour for companies and households. Smart meters are rolled out and increasingly used in demand response programmes in all demand sectors. New demands for electricity in heating (heat pumps) and transport (electric vehicles) are used to balance supply and demand. The electricity supply sector changes quickly. Initially this is in line with current policy plans, with high investment on onshore and offshore wind. After 2020, solar PV costs fall to below grid parity and a major paradigm shift occurs, with distributed solar becoming the dominant supply option before 2050. This change is facilitated by the availability of much lower cost electricity storage after 2030. Offshore wind remains important for winter power supply and some gas fired generation is retained for load balancing. Both PV and storage investment result in a major switch away from centralised investment and the dominance of large supply companies. Smart distribution grids become the main means of load balancing with the transmission grid of less importance. Lower cost storage assists the market penetration of both heat pumps and electric vehicles after 2030.

Energy headline strategies – narratives		
	Strategy name	**Example narrative**
EN3	**Local energy and biomass**	There is a continued emphasis on strong climate policies with targets generally met. Concerns about energy security continue. Both are addressed by increasing amounts of local investment, similar to solar world. But in this case there are no major technological breakthroughs and local energy plans use a wider range of energy sources, including more aggressive energy demand reduction and local biomass, both as a solid fuel and as biogas through the gas grid. Existing long term trends in demand change, 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. 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 limited. There is increased investment in heat networks in all large urban areas, using a combination of fuels, but largely biomass CHP. 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.
EN4	**Interconnected world**	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. 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 and increasingly used in demand response programmes in all demand sectors. In particular, new demands for electricity in heating (heat pumps) and transport (electric vehicles) are used to balance supply and demand. The electricity supply sector changes quickly. Initially this is in line with current policy plans. There is very large and rapid investment, especially in offshore wind. This 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.

Energy headline strategies – narratives		
	Strategy name	**Example narrative**
EN5	**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 which eventually become dominant.
EN6	**Local hydrogen**	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. Smart meters are rolled out and increasingly used in demand response programmes in all demand sectors. After 2030, this is increasingly important to manage the integration of power from distributed fuel cell generation. The electricity supply sector changes quickly, initially in line with current policy plans. There is early and rapid investment in offshore wind, primarily in the North Sea. Solar costs also decline and distributed solar PV is widely adopted. As the penetration of intermittent renewables increases, there are increasing problems with grid control at times of high production, mirroring similar trends in other EU countries. Attempts to address these issues through demand response, interconnection and storage fail for a variety of reasons. Electricity costs fall to zero at times of high production, resulting in a localised hydrogen production industry. This begins as a niche supplier of hydrogen for vehicles, but stimulates the growth of a major fuel cell boom for both transport and stationary applications. There are limited changes to the electricity grid, but the gas grid changes after 2030 from methane to using increasing proportions of hydrogen. Heat remains initially dependent on gas, but after 2030 this becomes more hydrogen dependent as local hydrogen production and fuel cell deployment increase. Transport fuel supply remains initially oil dependent. Electric vehicles prove unpopular and as hydrogen becomes increasingly available, fuel cell vehicles become more popular after 2030.

Energy headline strategies – narratives		
	Strategy name	**Example narrative**
EN7	**Electrification of heat and transport**	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. The electricity supply sector changes quickly, initially in line with current policy plans. There is early and rapid investment in offshore wind, primarily in the North Sea. Solar costs also decline and distributed solar PV is widely adopted. As the penetration of intermittent renewables increases, grid control is addressed primarily through 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.
EN8	**Nuclear & gas**	There is a declining emphasis on climate policies and long term targets are abandoned. Increased global uncertainty is the dominant driver of energy policy. These are addressed by large investments in indigenous resources and technology, first shale gas and then nuclear power. This ensures high 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 and increasingly used in demand response programmes in all demand sectors. The electricity supply sector changes, but initially only slowly as gas increases is market share. Low carbon generation options initially make little progress, but after 2030 there is renewed interest in nuclear technology, by which time costs have fallen substantially as a result of developments elsewhere in the world. There is then increased investment in nuclear in the UK. Throughout there is continued dominance of large companies. Electrification of heating and transport is very limited.

Energy headline strategies – narratives		
	Strategy name	**Example narrative**
EN9	**All in – diverse low carbon**	There is a continued emphasis on strong climate policies with targets met. Concerns about energy security continue and are addressed by large investments in demand reduction, low carbon electricity generation and biomass technologies. 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. New technologies allow efficient use of both biomass derived fuels and electricity in transport. Heating demands fall and are met by a combination of low carbon technologies, including renewable CHP district heating and heat pumps. 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. The rapid growth of offshore wind provides a huge resource for the whole of Europe. Declining energy demand allows the UK to become a large exporter, enabled by rapid development of interconnection.

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'.
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.

Transport headline strategies – narratives

	Strategy name	Example narrative
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'.
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.
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.

Water headline strategies – narratives		
	Strategy name	**Example narrative**
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.