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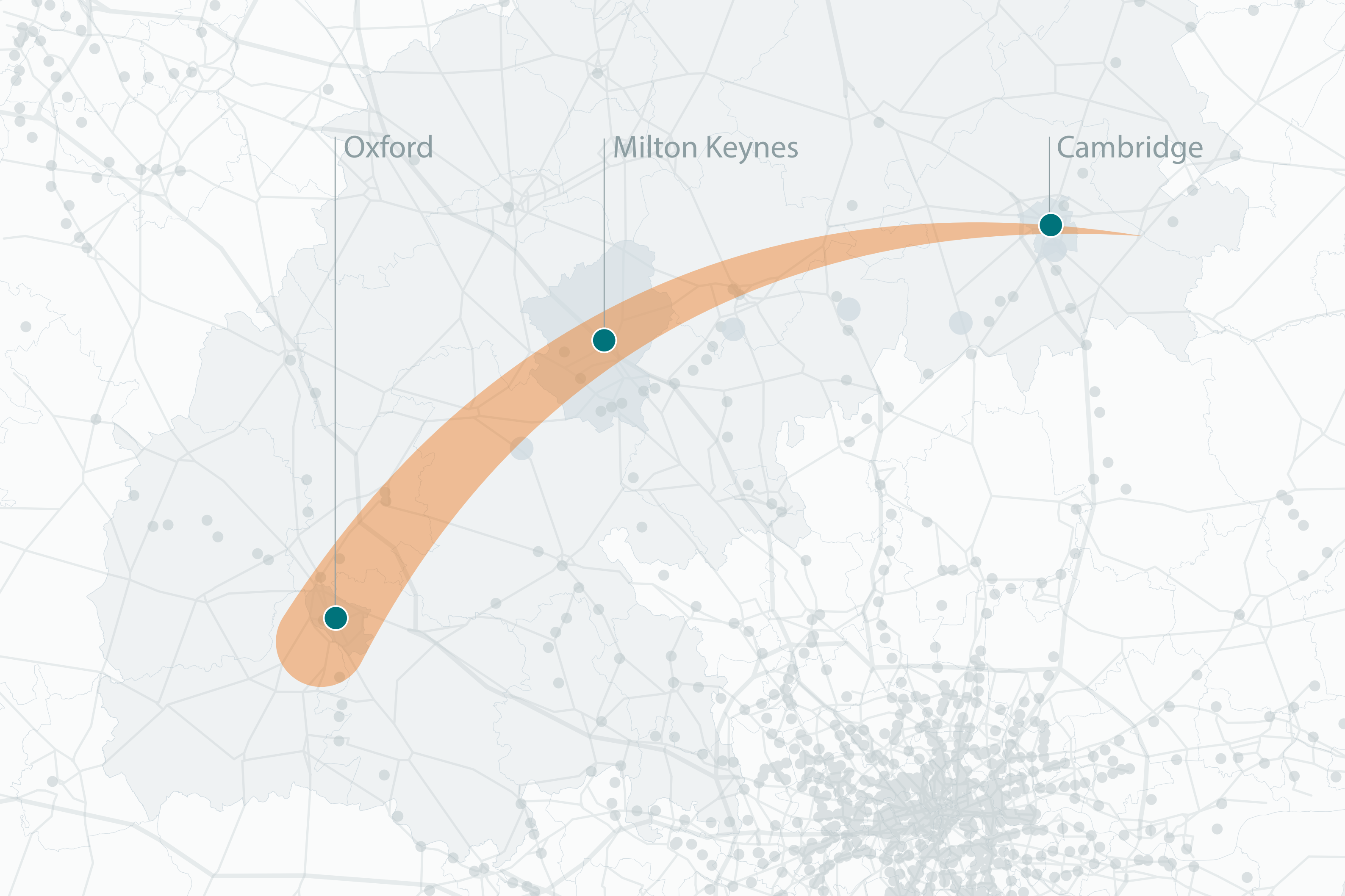

A sustainable Oxford-Cambridge corridor?

Spatial analysis of options and futures for the Arc

Full report

UKRI Engineering and Physical Sciences Research Council

Main contributors

Editors: Adrian Hickford[1], Tom Russell[2], Jim Hall[2], Robert Nicholls[1]

Scenarios / UDM / SIMIM: Adrian Hickford, Tom Russell, Alistair Ford[3], James Virgo[3], Nik Lomax[4], Andrew Smith[4], Stuart Barr[3]

Econometrics: Adam Brown[5], Pete Tyler[6], Ben Gardiner[5]

Transport: Milan Lovric[1], Simon Blainey[1]

Energy: Modassar Chaudry[7], Lahiru Jayasuriya[7]

Water: Barney Dobson[2]

Digital communications: Edward Oughton[2]

Urban drainage: Vassilis Glenis[3], Chris Kilsby[3], Stephen Birkinshaw[3]

Urban form: Nahid Mohajeri[2]

Natural capital: Alison Smith[2]

1. University of Southampton
2. University of Oxford
3. University of Newcastle
4. University of Leeds
5. Cambridge Econometrics
6. University of Cambridge
7. Cardiff University

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Executive summary

The Oxford-Cambridge Arc contains some of the fastest growing and most productive towns and cities in the UK. Home to 3.7 million people, over 2 million jobs and contributing over £110 billion of annual Gross Value Added (GVA) to the UK economy per year, the Arc has been designated as a key economic priority by the Government, aiming to build on established strengths in knowledge-intensive sectors, science, technology, high-value manufacturing and innovation. Increased population, employment and productivity are key drivers of future economic growth and prosperity, enabled by increased accessibility to services and employment, and increased connectivity between urban centres.

This report demonstrates how the ITRC-MISTRAL modelling suite NISMOD can provide independent systems-based analysis of the implications of future change, and provide new insights into the implications of the major policy themes related to population change and new transport infrastructure. The analyses are based around the development of the road and rail networks between Oxford and Cambridge, and three contrasting growth scenarios for new dwellings within the Arc. The future of the Arc is likely to be a combination of different types of development, but for ease of comparison we have examined the cases whereby development is focused either on (i) Expansion of existing settlements; (ii) in New Settlements; or (iii) is Unplanned so happens in a haphazard way across the Arc.

The allocation of new dwellings and population for each Arc scenario are modelled by assessing development suitability using a set of constraints and attractors, with future employment demand met by a combination of urban densification, urban fringe developments, new hinterland locations, and at significant new developments based around prospective transport hubs. While Expansion of existing conurbations is likely to impact on protected greenbelt areas, it is possible that careful planning could allow development of New Settlements, while still protecting greenbelt land and other important habitats in the Arc. However, a preliminary scoping assessment of the potential impacts of new development on natural capital and ecosystem services demonstrates that the footprint of the development is a critical factor. All development scenarios could lead to a significant loss of natural capital: the Baseline scenario has the lowest impact (20,000 hectares of new development), followed by the Unplanned scenario (30,000 hectares), the Expansion scenario (48,000 hectares) and the New Settlements scenario (58,000 hectares) which has the highest impacts. However, the potential loss of services per hectare is generally slightly higher for the Unplanned scenario as it has fewer environmental constraints. The natural capital assessment technique is still being tested, and further analysis will aim to explore a 'Green Vision' scenario that aims to reduce impacts on natural capital through more compact developments that protect existing natural capital assets and build in new green infrastructure.

The Expressway initially delivers some time savings for longer road journeys, such as between Oxford and Cambridge, but the fastest route choices more locally tend to remain on existing roads, depending on the origin and destination. For all growth scenarios, higher population implies higher levels of congestion, and while the planned road expansions and developments initially generate time travel savings, congestion levels and travel times will increase in the longer term if steps are not taken to manage demand for road transport and transfer passengers onto other modes of transport including rail and 'active travel' (walking and cycling). Notwithstanding high population growth, uptake of electric vehicles would result in a sharp decrease in carbon emissions and local air pollution in the longer term, although electrification will substantially increase electricity demand.

The vision of a carbon neutral Arc is achievable, given the current trends in generating increasing amounts of electricity from renewable sources and the potential for increased uptake of renewables within the Arc. The greatest challenge to achieving a carbon neutral Arc is how to heat new and existing buildings without using fossil fuels. We contrast an 'electric' strategy with a 'multi-vector' energy solution, which incorporates local heat networks, green gas and widespread use of electric heating. The mix of technologies enhances resiliency and operational flexibility compared to a heating solution that relies entirely on electricity; however, it is hindered by increased systems complexity, and high capital costs. The most cost-effective route to decarbonisation of heating may be transitioning to heat pumps, resistive heating and electric boilers, and running these on decarbonised electricity. However, there are barriers to such a future, such as the potential disruption to households during retrofitted installation, relatively high capital costs of low-carbon heat technologies, and potential gaps in engineering training and human capacity. A campaign to raise awareness of such technologies may help increase public confidence and uptake. It will be much more cost-effective to incorporate these technologies from the outset in the new buildings within the Arc, alongside improvements to energy efficiency and insulation to reduce the energy requirements of heating. Protecting and enhancing the carbon stored in vegetation and soils is also important in order to help achieve carbon neutrality in the Arc, though the potential impacts have not yet been quantified.

Population change only has a minor impact on demand for 5G infrastructure, which is largely driven by the changing nature of per user data consumption, particularly for on-demand video. Significant supply-side changes are expected in how mobile networks deliver data services, and a combination of deploying new spectrum bands utilising 5G technologies and increased network densification through Small Cells may be the most cost-effective and reliable means of delivery in dense urban areas. There are further cost efficiencies to be gained through coordinated planning of both fixed and mobile digital communications, particularly when building and maintaining other infrastructure sectors.

The Arc is served by four water companies, and if these companies are able to deliver on their plans for demand management and leakage reduction, future per capita demand for water will decrease, but population growth in the Arc is projected to cause an increase in total water use in the long-term. Without new infrastructure to improve supply, the risk of restrictions on water use doubles by 2050.

These risks can be somewhat mitigated through new reservoirs (as proposed by Anglian Water) and effluent reuse schemes (as proposed by Thames Water at Beckton in East London).

The scenarios considered are transformative. Baseline population growth takes the Arc from 3.7 million people in 2015 to 4.4 million in 2050; the higher growth Expansion and New Settlements scenarios consider up to 5.4 and 6.1 million people respectively by 2050. Strategies to significantly reduce the carbon emissions from heat and transport require sweeping technology transitions. Population growth drives increases in water demand despite per-capita reductions while the generally drier near-future climate scenarios contribute to increased risk of water use restrictions. Full-fibre and 5G broadband must prioritise coverage if they are to meet future expectations of digital connectivity.

The Arc region is not isolated. Population change, economic growth and their implications for infrastructure services in the Arc have wider impacts on a regional and national context. Some of the housing pressure within the Arc comes from demand in London and the South-East. Part of the motivation for the road and rail improvements comes from the need to move freight more effectively between the East of England, South West England and South Wales. North-south transport flows also affect congestion on the major roads in the Arc. Resilience to drought in the SWOX water resource zone is linked to the Thames system and London. Transmission-connected electricity generation across the country affects the cost, reliability and carbon intensity of electricity consumed within the Arc.

Changes in one sector have effects in others. Rapid vehicle electrification would reduce transport emissions and increase electricity demand from transport, while demand-side management (including from grid-connected vehicle batteries) is effective in reducing peak demand. Existing urban areas have opportunities for densification and challenges to upgrade, adopt or retrofit technologies. New developments present opportunities to build to the highest standards of energy efficiency, introduce heat networks, lay ducts for fibre and design sustainable drainage, but they also present challenges to preserve green corridors, minimise impacts on natural capital (including food production), design liveable places and build urban environments that can adapt and last.

In conclusion, this analysis of the Arc shows the benefits of an integrated analysis of infrastructure development, including sectoral interaction. The development and analysis of consistent scenarios including a range of possible urban forms illustrates the diverse ways the Arc may develop. Key interactions between sectors such as growing electricity demand for transport are also apparent as well as wider consequences of the Arc development such as in water supply.

This report shows how ITRC-MISTRAL modelling capabilities can be applied in a regional context. All this new information and these insights can inform the ongoing debate about how the Arc will proceed and the key policy decisions and actions that need to follow. The ITRC-MISTRAL modelling suite NISMOD is continuing to be developed for national and regional application within the UK and around the world.

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1. Introduction

The Oxford-Cambridge Arc has long-term potential to transform into a world-leading economic area and has been designated as a key economic priority by the Government, aiming to build on established strengths in knowledge-intensive sectors, science, technology, high-value manufacturing and innovation. The future vision for the region is one of continued growth, but this may be limited by a number of infrastructure constraints. The demand for housing throughout the Arc is high and house prices in Oxford and Cambridge are twice the national average. The delivery of housing stock for future growth across the Arc is already insufficient, with the current average of around 15,000 new dwellings per year falling short of the estimated requirement of 20,000 dwellings per year.[1,2] There is limited transport infrastructure linking the major conurbations which adversely affects connectivity. For instance, the east-west transport routes are restricted as there is no major road or railway linking Oxford and Milton Keynes, which extends journey times and constrains flows across the Arc.

With these aims and constraints in mind, the National Infrastructure Commission (NIC) have identified four inter-related policy themes which are important to facilitate future growth throughout the Arc: (i) Productivity – ensuring businesses and skills are supported to maximise the Arc's economic prosperity; (ii) Place-making – delivering sufficient affordable, high-quality homes, workplaces and community places; (iii) Connectivity – improving infrastructure for transport, digital connectivity, and utilities; and (iv) Environment – protect and enhance the natural environment.

The Infrastructure Transitions Research Consortium (ITRC) is a consortium of seven universities (Cambridge, Cardiff, Leeds, Newcastle, Oxford, Southampton, Sussex) led by Oxford and funded by the EPSRC, with significant inputs from others including Cambridge Econometrics. The original aim of the consortium was 'to develop and demonstrate a new generation of simulation models and tools to inform the analysis, planning and design of national infrastructure.' This report is one example of how the tools developed by ITRC can be applied to a specific region, to determine the effects of future change, and provide insight into the impact of changes in demand, growth and technology.

The ITRC's models, scenario analysis and geospatial design methodologies can help to explore and inform choices about how the Arc will be developed. This report focuses on the Arc as a case study to demonstrate the ITRC MISTRAL (multi-scale infrastructure systems analytics) assessment methodology and the multiple capabilities of our infrastructure systems modelling suite.

1 Savills (2016). The property market within the Cambridge – Milton Keynes – Oxford corridor.

2 5th Studio (2018). Cambridge, Milton Keynes and Oxford Future Planning Options Project: Final Report. Cambridge, UK.

The analyses are based around three contrasting growth scenarios for new dwellings within the Arc – expansion of existing conurbations, development of new settlements, and unplanned development – and the potential impacts of the introduction of new and enhanced transport infrastructure (an Expressway road and new rail routes connecting Oxford, Milton Keynes and Cambridge. We do not aim to provide specific answers to the many and diverse issues and challenges that face governing bodies, stakeholders, utility providers and residents of the Arc. Rather, this report offers insight into the potential effects of substantial growth in dwellings and population within a relatively limited and constrained region.

2. Development of the Arc

2.1 'The Arc' – a brief history

In March 2016, the National Infrastructure Commission (NIC) were asked by the UK Government to investigate the growth potential of the Cambridge – Milton Keynes – Oxford 'growth corridor' as a single, knowledge intensive cluster. The NIC aimed to provide guidance regarding appropriate planning for future growth, and subsequent associated reports focused on a number of topics, including the potential need for housing given a range of growth scenarios,[3] the nature, scale and potential locations of such housing growth,[4] the economic rationale for infrastructure investment in the corridor,[5] barriers and levers to implementing any future housing and infrastructure investment plan.[6, 7] Further documentation explores the options available and implications of enhanced transport connections,[8, 9] including an Expressway[10] to upgrade the road system connecting Oxford and Cambridge, and East West Rail,[11] providing a better rail service in the corridor, particularly between Oxford and Milton Keynes and within the eastern section between Bedford and Cambridge.

Since these consultation reports were produced, the definition of the corridor has changed. The original definition included 22 Local Authority districts (LADs), but in the recent MHCLG report[12] this definition has been adapted to exclude Swindon, Stevenage and East and North Hertfordshire, and extended to include areas surrounding Peterborough, Corby and High Wycombe, and is now referred to as the Oxford-Cambridge Arc. Nevertheless, the analyses in these earlier consultancy reports remain largely valid and informative.

3 Savills (2016). The property market within the Cambridge – Milton Keynes – Oxford corridor.

4 5th Studio (2018). Cambridge, Milton Keynes and Oxford Future Planning Options Project: Final Report.

5 SQW & Cambridge Econometrics (2016). Cambridge, Milton Keynes, Oxford, Northampton Growth Corridor: Final Report for the National Infrastructure Commission.

6 AECOM (2018). Report for the National Infrastructure Commission: Cambridge – Milton Keynes – Oxford Arc.

7 Metro-Dynamics (2017). NIC – Finance and investment workstream report.

8 ARUP (2017). NIC – Transport workstream report.

9 Steer Davies Gleave (2017). Transport Infrastructure Assessment – Oxford, Milton Keynes, Cambridge, Northampton Growth Corridor.

10 Highways England (2018). Oxford to Cambridge Expressway – Strategic Outline Business Case.

11 East West Rail (2019). Bedford to Cambridge Route Option Consultation: Technical Report.

12 MHCLG (2019). The Oxford-Cambridge Arc Government ambition and joint declaration between Government and local partners.

2.2 Economic rationale

The Arc, bounded by two of the world's leading universities, contains some of the fastest growing and most productive towns and cities in the UK. Home to 3.7 million people, over 2 million jobs and contributing over £110 billion of annual Gross Value Added (GVA) to the UK economy per year, the Arc has been designated as a key economic priority by the government, aiming to build on established strengths in knowledge-intensive sectors, science, technology, high-value manufacturing and innovation. Increased population, employment and productivity are key drivers of future economic growth and prosperity, enabled by increased accessibility to services and employment, and increased connectivity between urban centres.

The universities and research and development facilities in Oxford and Cambridge support health and education sectors, and together with tourism provide a large source of income to the region. The specialisation and commercialisation of high-tech research, particularly in Cambridge, also contributes to the Arc's economic prosperity and reputation. Milton Keynes has a large professional, business and technical service base. Northampton has more affordable property, good transport and digital connectivity, which offers an attractive location for companies and start-ups.

2.3 Current state of the Arc

The Oxford-Cambridge Arc (or 'the Arc') is comprised of four county councils (Buckinghamshire, Cambridgeshire, Northamptonshire and Oxfordshire), 26 district councils and unitary authorities, and the combined authority of Cambridgeshire and Peterborough (see Figure 1). In addition, there are a variety of stakeholders, including four Local Enterprise Partnerships (LEPs),[13] England's Economic Heartland,[14] and many others. Of the 3.7 million people living in the Arc, 1.3 million live in one of the seven major urban centres of Oxford, Bedford, Luton, Milton Keynes, Northampton, Peterborough and Cambridge.

Proposals for the Arc have begun to take shape over recent years, culminating in the combined aims of central government and the local area to give a "commitment to providing new strategic infrastructure, matched with an ambition and commitment at a local level to deliver major housing growth and create places in which people want and can afford, to live and work".[15] This is reflected in the joint declaration between Government and local partners on future planning in the Arc.[16]

13 Oxfordshire Local Enterprise Partnership (OxLEP); Buckinghamshire Thames Valley Local Enterprise Partnership (BTVLEP); South East Midlands Local Enterprise Partnership (SEMLEP); The Business Board of the Cambridgeshire and Peterborough Combined Authority.

14 www.englandseconomicheartland.com

15 National Infrastructure Commission (2018). Partnering for Prosperity: A new deal for the Cambridge-Milton Keynes-Oxford Arc.

16 MHCLG (2019). The Oxford-Cambridge Arc: Government ambition and joint declaration between Government and local partners.

Figure 1: Outline of the Arc.

Central to this shared vision is the development of one million new homes across the Arc by 2050, the provision of an east-west Expressway road, and major improvements to the East-West rail routes connecting Oxford, Milton Keynes, Bedford and Cambridge. Whilst these proposals have been established, there are many remaining questions about how the Arc vision will be implemented in different places and whether goals of growth, prosperity and sustainability are achievable in practice.

Delivering such an ambitious growth plan across traditional boundaries is a significant challenge and requires a long-term, cross-cutting, integrated strategic plan with collaborative governance and investment mechanisms for planning and infrastructure. Such a plan should provide a clear vision for future change, with a pipeline of planned future investments and specific delivery milestones which are reviewed and adapted at regular intervals.

There is a need for a systematic and evidence-based approach to explore and analyse possible futures, assess the potential impacts of future decisions, and inform the development of a credible shared vision. The ITRC has conducted detailed spatial scenario analysis in order to explore these issues.

3. Applying the ITRC MISTRAL assessment methodology

The ITRC first developed the National Infrastructure Systems Model (NISMOD) to test and optimise long-term national plans for infrastructure provision, including energy, transport, digital, water and waste infrastructure.[17] The second phase of the ITRC research programme, MISTRAL, further developed NISMOD to examine sub-national infrastructure initiatives such as the Arc. NISMOD therefore now offers the capability to quantify the implications of changing local needs for infrastructure services, within the context of the national 'big picture' of population change, economic growth, technological innovation and climate change.

NISMOD is a system-of-systems model made up of simulation models of key infrastructure sectors (water, transport, energy and digital – see Box 1) and the interdependencies between them. NISMOD uses scenarios of population, economics, urban development, climate and hydrology to explore the ways in which needs for infrastructure services might evolve in future and options for how those needs could be met. This combination allows simulation and exploration of how infrastructure services may be provided, and how demand for infrastructure services may be managed in different possible futures (Figure 2). Related ITRC research provides strategic insights into urban development, natural capital and urban drainage.

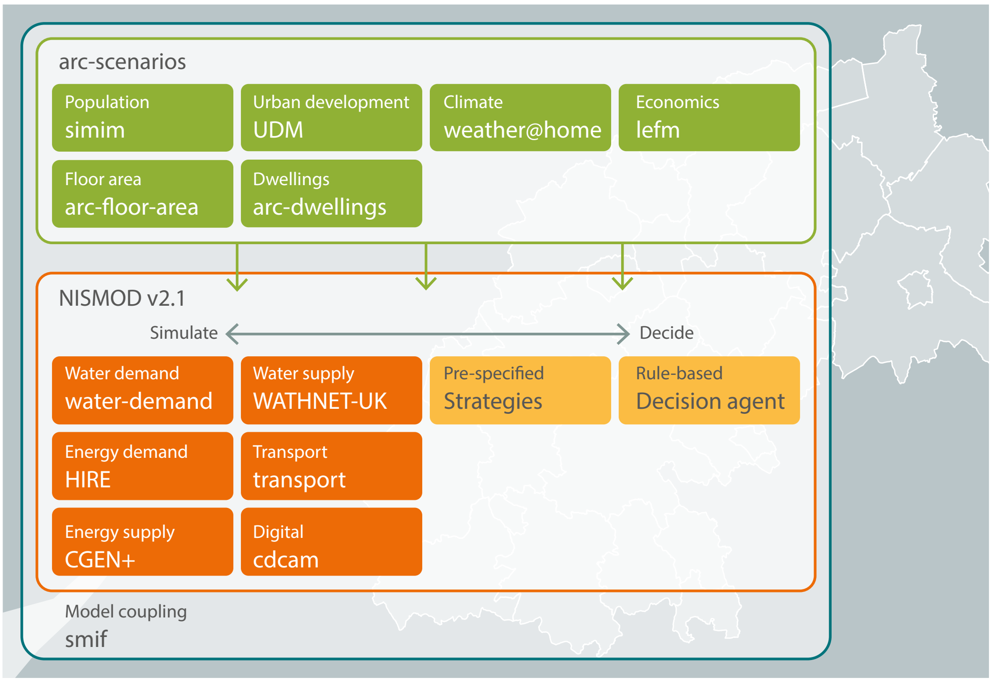


Figure 2: ITRC MISTRAL model components for the Arc assessment.

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

Box 1: NISMOD – the ITRC MISTRAL key infrastructure modelling suite

The following provides very brief overview of the sectoral models used in NISMOD. Further information on the modelling suite is available in an online Appendix[18] at www.itrc.org.uk

ENERGY: Our energy supply model is a modified version of CGEN[19] and includes both transmission and distribution of electricity, natural gas, hydrogen and heat supply systems and their interactions. The new local 'energy hub' model developed during the MISTRAL programme enables exploration of options for local energy generation and storage, providing the capability to design and optimise a carbon neutral Arc.

WATER: Our water resource system model simulates all major water supply assets in England and Wales (reservoirs, boreholes, transfers, water treatment works, pumped storage, desalination plants and river abstraction points) using Wathnet simulation software. Wathnet predicts whether water can be reliably supplied to the Arc, under a range of different water demand and climate change scenarios.

TRANSPORT: We have developed a national-scale model of the road and rail transport network. The model forecasts transport demand and congestion, providing predictions of travel times, travel costs and capacity utilisation.

DIGITAL COMMUNICATIONS: We have developed models of the coverage and cost of providing a range of standards of fixed and mobile digital coverage in the Arc. Our 5G assessment model undertakes system-level evaluation of wireless networks, quantifying the capacity, coverage and cost of deployment strategies. The network capacity and coverage (and cost of investment in improvements) are estimated using cellular site density, spectrum usage, and technology generation (4G or 5G).

The ITRC MISTRAL assessment is a systematic, integrated approach which takes contrasting illustrative scenarios of the large number of different possible development patterns and choices and examines the implications for infrastructure needs within the Arc and nationally. At this stage we have not yet investigated the wide range of detailed choices within the Arc. Rather, this study selects a few illustrative examples to explore the many possible combinations of future scenarios, and uses NISMOD to provide insights concerning these different choices.

The modelling process has two major steps. First the scenarios are selected or generated, then the infrastructure simulation models are run to estimate future demand for services and to evaluate strategies for supply.

18 Model description appendices available on the ITRC website: www.itrc.org.uk

19 Chaudry, M., Jenkins, N., Qadrdan, M., & Wu, J. (2014). Combined gas and electricity network expansion planning. Applied Energy, 113, 1171–1187.

Within the scenarios, there are three main strands: (i) scenarios which represent uncertainties for particular infrastructure sectors, for example changes in digital data demand or uptake of electric vehicles; (ii) socio-economic scenarios, which start with regional dwelling completions and economics (GVA, productivity and employment), leading to changes in population, floor area and patterns of urban development; and (iii) climate (temperature, precipitation and wind speed) under a near-future scenario, which also drives future variability in river flows. The socio-economic and sector-specific scenarios represent the key drivers of demand for infrastructure services, which are calculated using the digital, transport, energy demand and water demand models. The digital, transport, energy supply and water supply models then gather service demands, along with climate and hydrological variables, in order to simulate the systems which supply those services.

Infrastructure decisions are either (i) pre-specified as strategic plans for infrastructure interventions, where different strategies may be tested under various scenarios, or (ii) defined by a rule-based decision model, which is parameterised and used to generate actions in response to simulation outputs (for example, adding mobile cells in areas where demand is highest).

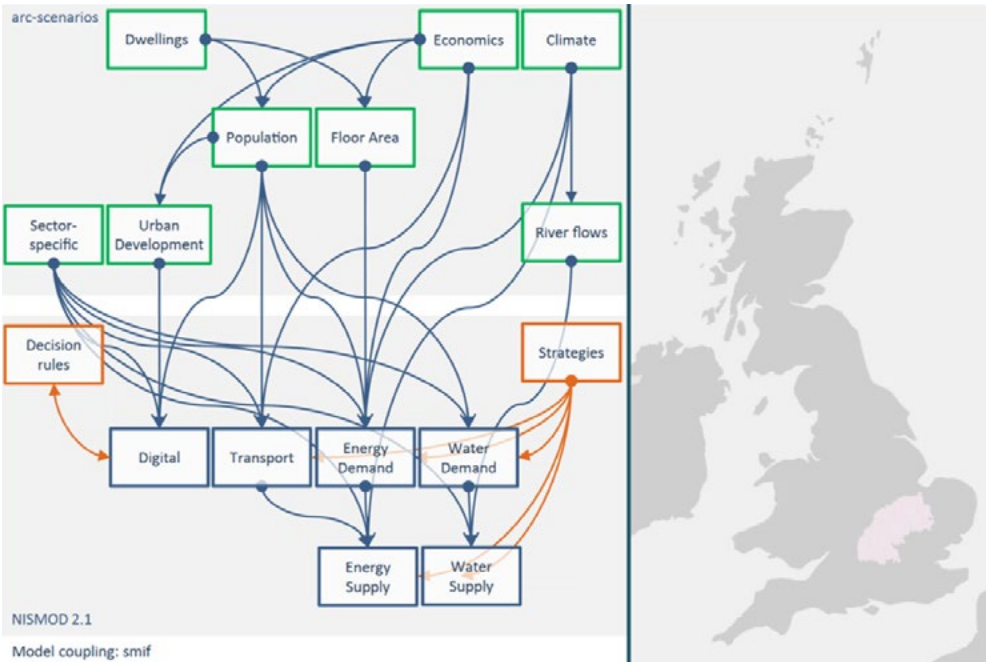


Figure 3: Data flow for Arc scenario generation and NISMOD: scenarios and strategies provide inputs to coupled infrastructure system simulation models.

In this report, we focus on two of the NIC's policy themes which represent critical challenges for the Arc: (i) the impact of the predicted growth in population brought about by providing new housing, and (ii) the impact of new transport infrastructure (i.e. the Expressway and East West Rail) which allows greater connectivity within the Arc.

4. Options for future change

These are a vast range of potential futures that could occur as the Arc develops into the future. This report aims to present an example of the capabilities of the NISMOD modelling suite by assessing a limited sample of distinct future options for the Arc. These involve specific and distinct assumptions (and choices) regarding the development of the transport infrastructure and the types and locations of new dwelling developments (Section 5).

4.1 Major new transport infrastructure

Improvements to the transport links between Oxford and Cambridge are a key aspect of the future vision for the Arc. In 'Partnering for Prosperity', the NIC state that the Expressway will "enhance connectivity across the Arc, expanding the labour markets of key towns and cities, as well as improving connections with international gateways".

Both road and rail improvements are currently proposed. The Expressway will comprise grade-separated dual carriageway between the A34 near Oxford and the A14 near Cambridge, including a proposed new road link between the M40 near Oxford and the M1 at Milton Keynes. East West Rail (EWR) will link Oxford and Cambridge via Bicester, Milton Keynes and Bedford, with opportunities for several new stations along the route.

There are important choices about these new transport routes which have yet to be finalised, and decisions about the location and density of new developments could result in a range of outcomes. At the time of writing, no decision has yet been made regarding the specific routes of the Expressway or East West Rail lines. We have selected the road and rail options shown below to include in our assessment. Other options are not considered in this study, but this does not imply those options are less likely to be chosen as the preferred routes. Any alternative option could be analysed within NISMOD.

Highways England propose several options for new road links and improvements around Oxford and between Oxford and Milton Keynes. Our assessment considers route B1, which goes to the west and north of Oxford, broadly via Bicester to Milton Keynes. A single corridor has already been identified for improvement between Milton Keynes and Cambridge (see Figure 4).

Network Rail propose options for rail stations and links towards the eastern end of the Arc, along the Bedford to Cambridge central section of EWR. Of the five options currently under discussion, we consider route A, which passes through Sandy and Bassingbourn (see Figure 4). The western section phase 1 between Oxford and Bicester is already operational, and the western section phase 2 is planned to reinstate and upgrade links to Milton Keynes, Bedford and Aylesbury.

We assume operational timings for each of the transport schemes: that the Expressway is operational by 2030, EWR Phase 2 is operational by 2025, and the Bedford-Cambridge ('Central') stretch by 2030 (see Figure 5).

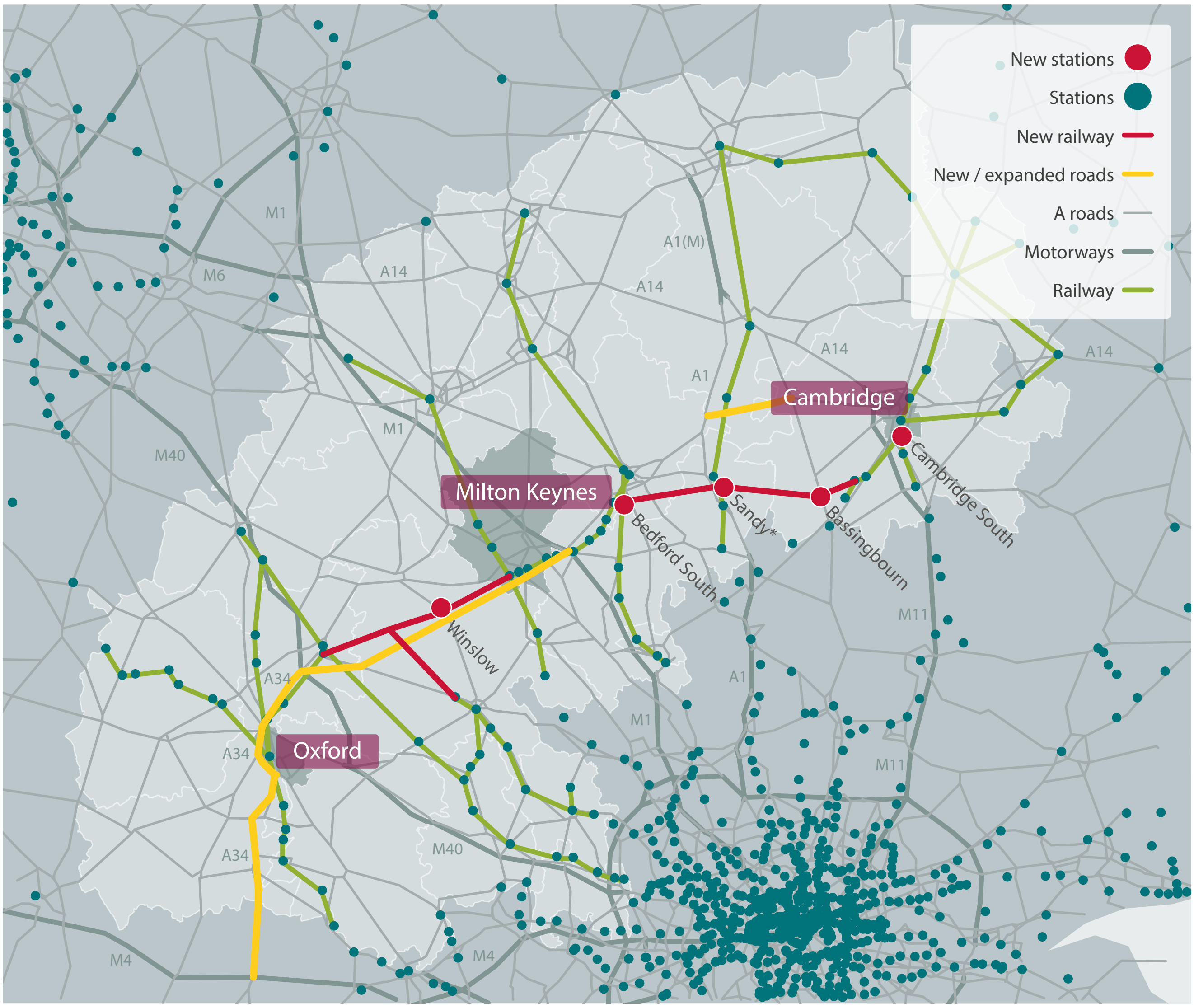


Figure 4: Expressway route B1 (marked in yellow) Oxford to Milton Keynes and East West Rail route via Sandy and Bassingbourn selected for analysis.

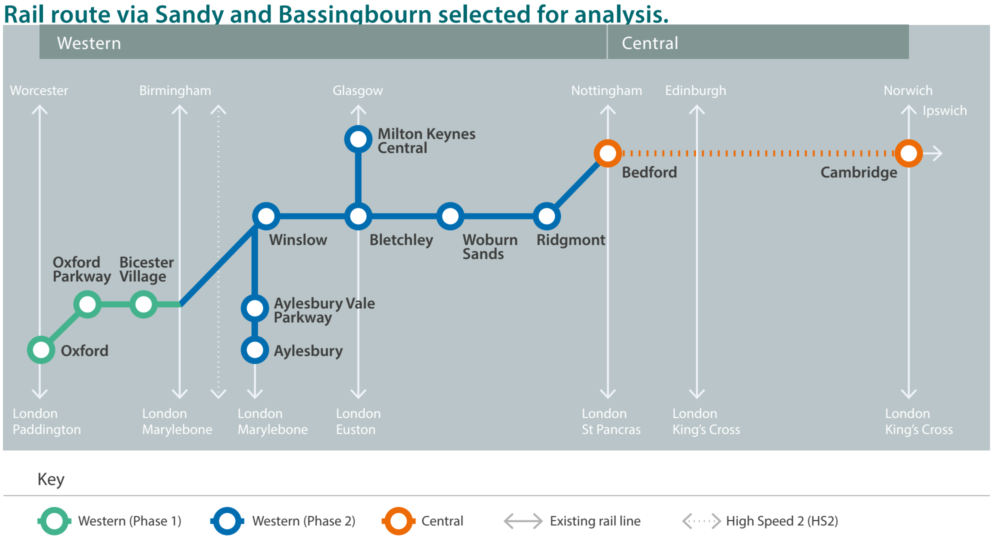


Figure 5: East West Rail planned connections (adapted from East West Rail https://eastwestrail.co.uk/the-project).

5. Scenarios of future development

As well as the transport options, there are many possible future development patterns and choices for the Arc. Scenarios of future needs for housing have been developed as part of the NIC consultation from 2016 to 2018. This projected a high growth scenario of 23,000 new dwellings per annum to meet needs within the Arc. This high growth scenario also projected an additional 7,000 dwellings per annum to relieve pressure from London and the South East. Our study adopts these same scenarios of higher developmental growth of both 23,000 and 30,000 new dwellings per annum. For a lower baseline scenario we assume 14,460 dwellings per annum, which is the average number of new dwellings completed in recent years.

The location and types of new dwellings are a key choice for the development of the Arc. There are many different ways in which a given number of new dwellings could be distributed across the Arc. Several diverse typologies of growth were set out in the 5th Studio report[20] based on urban intensification, linked places, and autonomous places. That report also presented a range of spatial scenarios for the future housing development: new settlements (e.g. one large city of around 2 million residents, two medium cities of around 1 million residents each, six towns of around 325,000 residents each or fifty new towns of around 40,000 residents each), and expansion of current conurbations (either through concentric expansion, or connecting two urban centres to create a larger conurbation).

We have used these typologies to develop our spatial scenarios for new dwellings to illustrate two contrasting possibilities: (1) expansion of existing conurbations, and (2) the development of new settlements. NISMOD could be used to analyse many different variants of spatial development.

Here, we consider 'Expansion' and 'New Settlements' for both 23,000 and 30,000 new dwellings per annum. We compare these planned growth scenarios with a 'Baseline' scenario based on recent average dwellings completions. We also consider an 'Unplanned' development scenario in which new housing development takes place at a rate of just under 19,000 new dwellings per annum, in response to the new transport infrastructure, but developments are allowed to occur on an ad hoc basis without an overall spatial vision. This range of spatial scenarios is summarised in Table 2.

For comparison, Figure 6 displays these levels of housing provision against the number of completions within the Arc since 2001.

We assume that no new large settlements are created in the Baseline scenario. However, ad-hoc developments occur throughout the Arc, reflecting the high land-values and commercial opportunities of new residential developments and the Spatial Attractors and Constraints delivered by the current planning system administered by local authorities.

20 5th Studio (2018). Cambridge, Milton Keynes and Oxford Future Planning Options Project: Final Report.

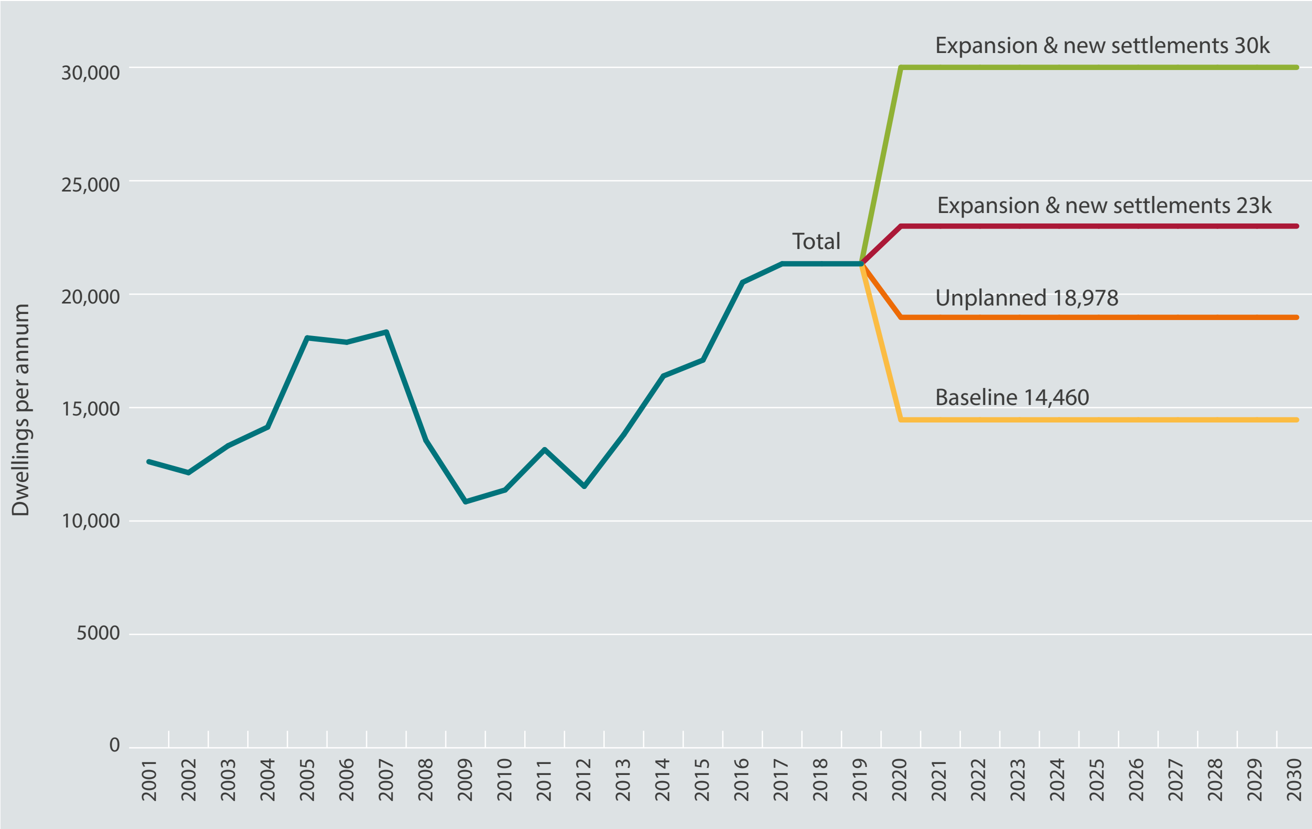


Figure 6: Recent rate of new housing provision in the Arc, compared with the future scenarios analysed in this study.

Unplanned development

For the 'Unplanned' scenario, we explore the implications of ad-hoc construction driven by market fundamentals. In particular, the role of the Expressway and East West Rail in creating new attractive locations due to the increase in connectivity. Combined with a laissez-faire planning policy which enables a proliferation of uncoordinated developments, a significantly higher land-take due to the absence of planning enforcement, this scenario enables an exploration of the sustainability of such an approach.

Thus, the number of new dwellings for LADs not adjacent to the new transport infrastructure is the same as in the Baseline (average additions 2007-2017). For LADs adjacent to the new transport infrastructure (Cherwell, Oxford, Aylesbury Vale, Bedford, Milton Keynes, Cambridge, Huntingdonshire, South Cambridgeshire), each LAD builds at same rate as the peak year 2007-2017. This equates to about nineteen thousand new dwellings per annum (18,978) to 2050, resulting in around 2.2 million total dwellings across the Arc in 2050.

Expansion of existing settlements

For the Expansion scenarios, we have assumed that the new dwelling completions are divided among the major conurbations with Milton Keynes taking 30% of the new development, Luton and Bedford sharing 30% and the other 40% split between Oxford, Cambridge, Northampton and Peterborough. The implications of these choices are set out in Section 5.2.

30,000 new dwellings per annum

Baseline levels of completions continue (14,460 per annum), but additional housing (15,340 per annum) is built to bring the annual new completions to 30,000 starting in 2020. This results in a total of 2.5 million dwellings in 2050.

New settlements

For the New Settlements scenarios, we have assumed that there will be five new towns or cities situated near the new transport infrastructure, in locations which seem geographically appropriate for development (see Figure 9):

- Cherwell (North of Bicester)
- Aylesbury Vale (South of Winslow)
- Central Bedfordshire (North of Cranfield)
- Central Bedfordshire (East of Sandy)
- South Cambridgeshire (North of Bassingbourn)

30,000 new dwellings per annum:

From 2020, growth is slowed in existing settlements, decreased to 50% of Baseline (7,230 per annum). The other 50% of Baseline (7,230) plus 15,340 per annum dwellings are split evenly across five new settlements. Thus, each new settlement expands by 4,534 dwellings per annum (from 2020), and has 140,554 dwellings in 2050 (for comparison, Milton Keynes in 2016 has 110,600 dwellings). This equates to thirty thousand new dwellings per annum to 2050, resulting in around 2.5 million total dwellings across the Arc in 2050.

5.1 Economic scenarios

The NIC report, using numbers generated by Cambridge Econometrics, laid out an ambition for an additional 350,000 knowledge sector jobs to be located within the Arc by 2050. This represents an increase of 50% over existing knowledge sector employment. This is an ambitious target, however it is not unprecedented. The knowledge economies of Oxford, Cambridge and Milton Keynes have all grown rapidly over the past half-century, and this rate of growth represents a continuation of past trends, rather than a step-change.

However, all three economies are currently constrained by physical factors, and several significant infrastructural changes are required to maintain this momentum, including the provision of space and premises for these new and expanded industries. If this new space for employment is to be provided, it will likely be achieved by a combination of urban densification, urban fringe developments, new hinterland locations, and significant new developments based around prospective new stations along the planned EWR network. It is likely that a combination of all of these development sites would be required to house this level of new specialised employment.

The types of premises required would be dependent upon the exact sectors that are planned to expand. For information on these, we are able to draw on the recently published local industrial strategies of the two LEPs and Combined Authority, shown below.

Local Industrial Strategy	Targeted Emerging Technologies
Oxfordshire LEP	• **Digital Health** • **Space-Led Data Applications** • **Autonomous Vehicles** • **Quantum Computing**
South East Midlands LEP	• **Autonomous Vehicles** • **Advanced Manufacturing** • **High-Performance Engineering**
Greater Cambridge & Greater Peterborough	• **Life Sciences & Biotech** • **AI & Big Data** • **Semiconductor Devices** • **Advanced Materials**

Translated to SIC codes, these correspond to expansion of employment in the following sectors:

- Scieeering and Technical Support Services (71, 74)
- Manufacturing (C, 10–33)

Additional employment growth in related and supporting knowledge-service sectors, such as legal and accounting, finance, and management consulting, can also be anticipated.

The range of employment space required varies from high-quality offices and industrial premises, to highly-specialised laboratory space.

5.1.1 Spatial distribution of new employment sites

In the Baseline scenario, the types of employment likely to grow are similar to that of today, with high tech engineering, bioscience and electronics focussed around Oxford and Cambridge, and back office and services sectors in Milton Keynes, and limited growth in the spaces in between the major cities. In the expansion scenarios, significant new employment space would have to be developed. This is likely to be strongly influenced by the location of new expressway junctions and, particularly, new rail stations.

Our projections of where the new employment could be located is illustrated in Figure 7. Exact locations of new premises are unknown and depicted for illustrative purposes only.

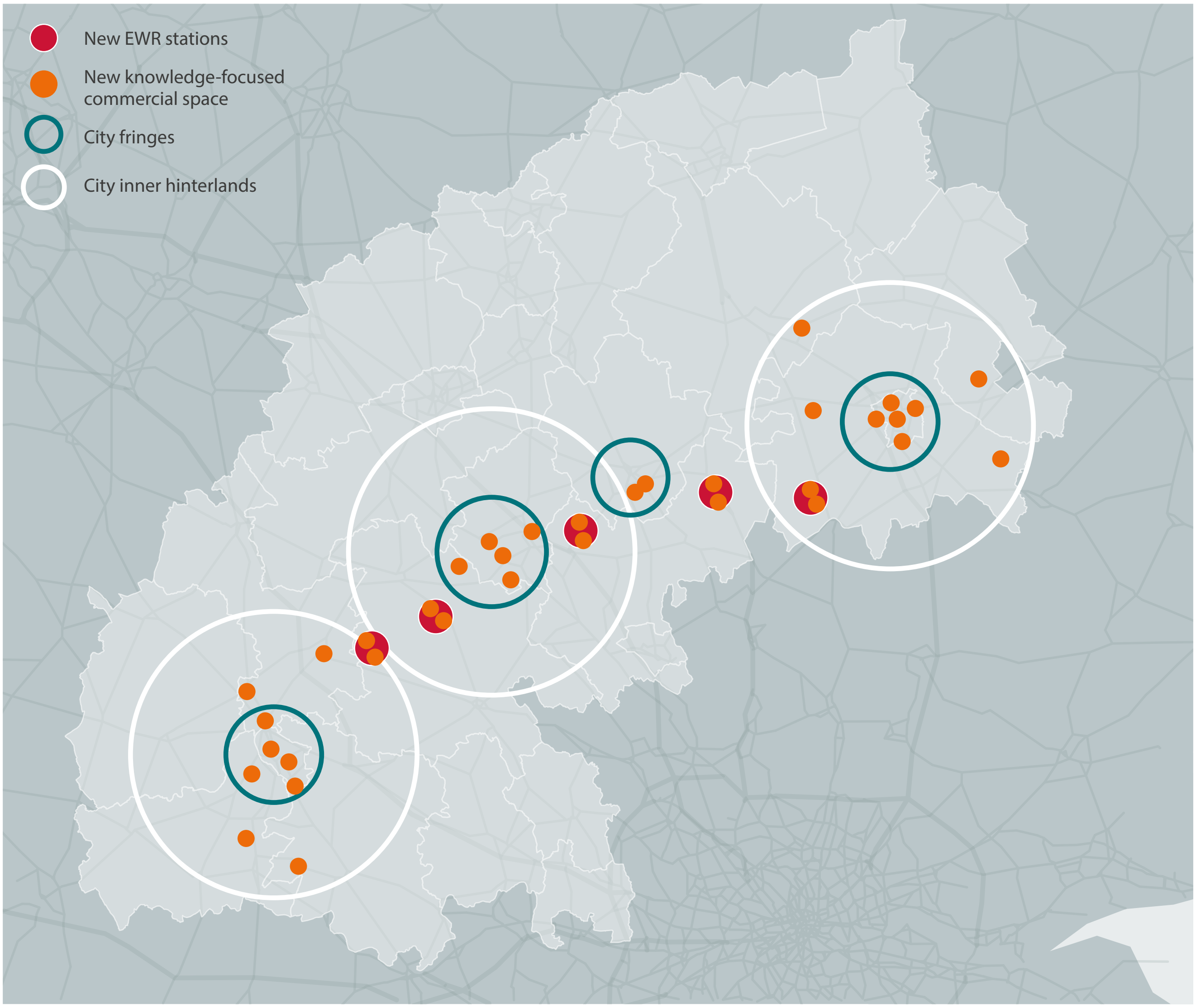


Figure 7: Indicative example showing potential new employment centres.

Table 1 shows the allocation of knowledge sector employment sites for use in the model.

In addition to the projected new knowledge-sector employment, there will be a corresponding increase in other non-tradable service sector jobs (e.g. retail and public sector). These jobs are assumed to be located in close proximity to the populations they serve. Therefore, whereas the spatial distribution of Knowledge-sector employment sites is assumed to be approximately invariant to different expansion scenarios, the distribution of non-tradeable sector employment is assumed to closely match the spatial distribution of new housing sites in each scenario.

The overall employment and GVA projections were calculated using an input-output modelling approach, in which growth in population and knowledge-sector employment were treated as exogenous inputs. Demand for non-tradeable services and other supporting activity were then derived, along with an estimate of future productivity growth for each scenario.

Table 1: Knowledge sector employment allocation scenario

Potential Site	Additional Knowledge Sector Jobs
Central Cambridge densification	20,000
Cambridge Fringe (<5km)	30,000
Cambridge Hinterland (>5km)	40,000
Central Oxford densification	20,000
Oxford Fringe (<5km)	30,000
Oxford Hinterland (>5km)	40,000
Central MK densification/expansion	20,000
MK Fringe (<5km)	30,000
Along EWR Route:	
New Station: North of Bicester	20,000
New Station: South of Winslow	20,000
New Station: North of Cranfield	20,000
New Station: South Bedford	20,000
New Station: East of Sandy	20,000
New Station: North of Bassingbourn	20,000
Total	350,000

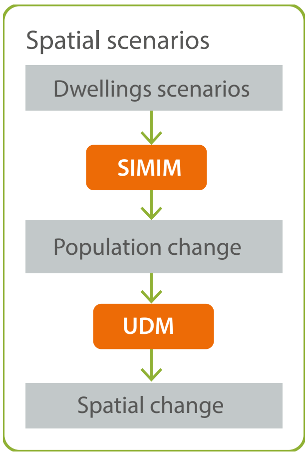


Figure 8: Generating spatial scenarios of population and development.

5.2 Simulating new development scenarios

The additional dwellings, people and jobs in the Arc region can be accommodated in a number of different ways depending on planning policies.

We use two related models to translate the dwellings scenarios into population change and to assign new development to appropriate land (Figure 8). SIMIM (Spatial Interaction Models of Internal Migration) determines the levels of population migration to and within the Arc, given the relative attractiveness of different locations. UDM (Urban Development Model) takes SIMIM outputs, and simulates the spatial patterns of new building development given land availability and other spatial constraints and attractors.

Several possible constraints on new developments are considered, including existing developments, greenbelt, flood plains and areas protected for environmental reasons. We considered different scenarios for the rigour with which these constraints are applied (Table 2). This does not mean that we advocate the existence or removal of constraints.

It simply demonstrates NISMOD's capability to analyse policies that modify where land is made available for development.

An example of the UDM outputs is shown in Figure 9. This highlights the different levels of development suitability and land availability given different attractors and constraints. For example, in New Settlements development of greenbelt is highly restricted, but such restrictions are not imposed for the Expansion scenario.

Table 2: Comparison of spatial scenarios for new dwellings

Scenario	Dwellings per annum	Transport assumptions	Attractors	Development constraints*
Baseline **Average 2007-2017 additional dwellings** **(Source: MHCLG)**	**c.14,500**	**No Expressway** **No East West Rail**	**Proximity to public transport, road network current development** **Accessibility to employment**	**All constraints in place** **Greenbelt developed = 0 ha**
Unplanned development **Slightly higher growth assumed along new transport corridors** **(Peak additions 2007-2017, Source: MHCLG)**	**c.19,000**	**Expressway by 2030** **East West Rail Phase 2 by 2025** **Bedford-Cambridge by 2030**	**Proximity to current development existing transport nodes and new stations, existing and new roads** **Accessibility to employment**	**Some greenbelt development allowed in LADs near new transport infrastructure** **Construction allowed on some protected habitats and higher flood risk** **Greenbelt developed = 2160 ha**
New settlements **Major growth in five new urban conurbations**	**23,000 and 30,000**	**Expressway by 2030** **East West Rail Phase 2 by 2025** **Bedford-Cambridge by 2030**	**Proximity to new development locations, existing transport nodes and new stations, existing and new roads** **Accessibility to employment**	**Construction allowed on some protected habitats near new settlement locations** **Greenbelt developed = 475 ha**
Expansion **Major growth around existing urban centres**	**23,000 and 30,000**	**Expressway by 2030** **East West Rail Phase 2 by 2025** **Bedford-Cambridge by 2030**	**Proximity to current development, existing transport nodes and new stations, existing and new roads** **Accessibility to employment**	**Construction allowed on greenbelt** **Greenbelt developed = 12480 ha**

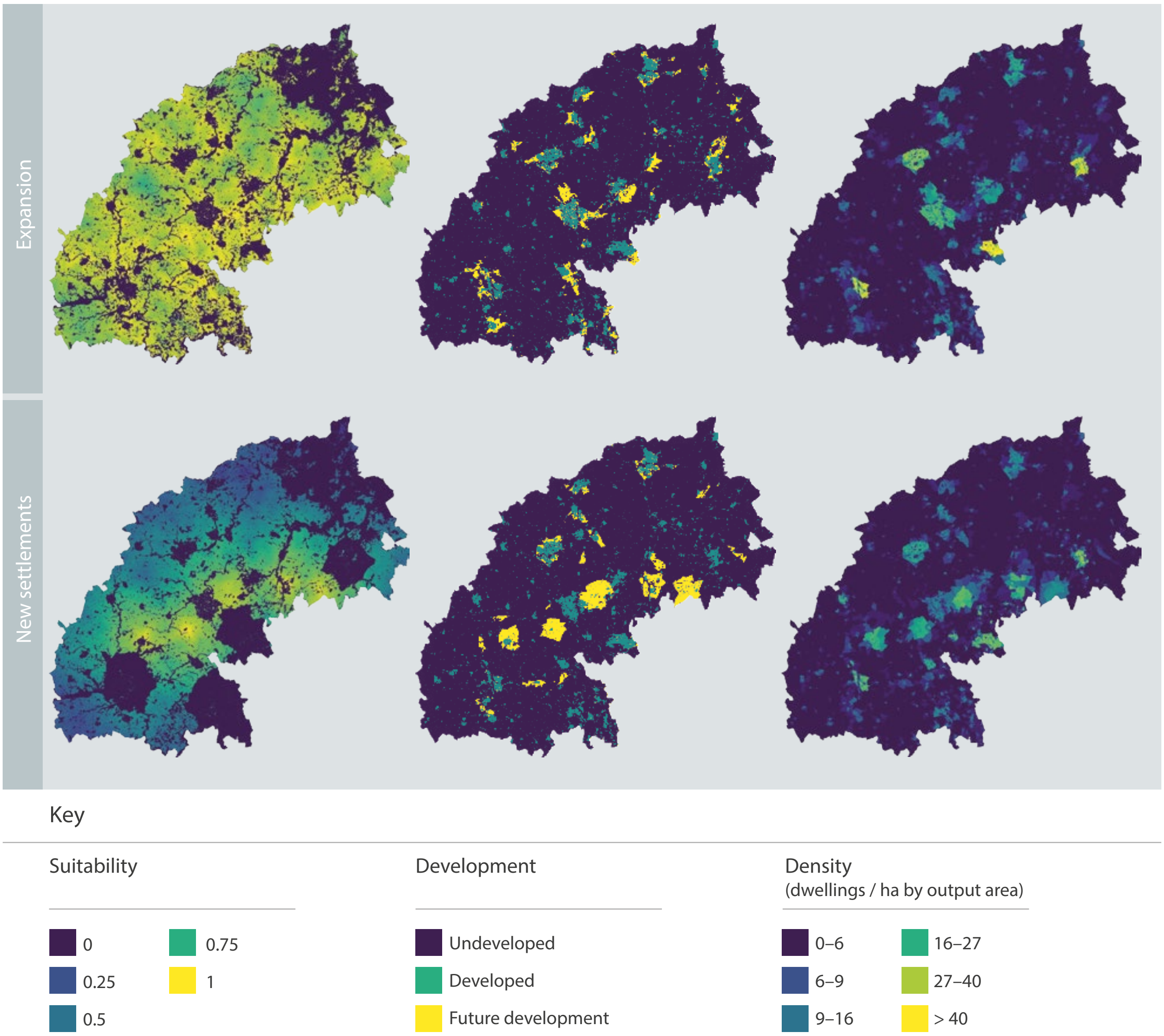
* The constraints considered are as follows: Greenbelt areas, Battlefields, Scheduled Ancient Monuments, SSSI, Priority Habitats, Local Nature Reserves, National Nature Reserves, World Heritage Sites, EA Flood Zone 3, Currently developed areas, Water bodies.

For the Expansion scenario, there are large increases in development and population density in areas around existing settlements, with currently-protected land including greenbelt surrounding Oxford and Cambridge being developed.

For the New Settlements scenario, each new conurbation implies a 180% increase (compared to Baseline) in the amount of land development. There is significantly less sacrifice of the greenbelt than for the Expansion scenario, suggesting that careful planning could allow development, while still protecting greenbelt land and other important habitats in the Arc. However, the preliminary assessment of the impacts on natural capital (see Section 6.8) shows that the impacts are greater for the New Settlements scenario because a larger area is developed.

The use of a spatial development model also allows an assessment of the density that new development must achieve in order to accommodate the projected population increases across the Arc. In some cases planning constraints mean that very little land is available and thus densities are high. In the Expansion scenario, for example, the required population for new development in Oxford reaches 400 people/hectare compared to 50 people/hectare across that local authority area at present. This shows the tension between protecting valuable land and freeing up enough development space to allow construction at an acceptable density. Figure 9 Example UDM outputs for New Settlements 30k and Expansion 30k scenarios for 2050

Figure 9: Example UDM outputs for New Settlements 30k and Expansion 30k scenarios for 2050.



6. Related analysis

There are related analyses within ITRC MISTRAL which can be applied to help understand future changes within the Arc. Specifically, we can consider the nature of the urban form of future developments, and the impacts on natural capital.

6.1 Urban form

Existing population centres within the Arc are likely to undergo significant future expansion, with corresponding investment in intra-city transport infrastructure unlocking a high level of economic growth. Some of this expansion is likely to be in the form of densification, whereby additional dwellings are built within existing urban areas, primarily on brownfield land and/or greenfield land. It is important that new neighbourhoods harmonise with the existing ones, so that new dwellings should not be in complete visual or typological contrast to the existing ones.

The aim of this aspect of MISTRAL is (i) to develop a machine-learning (ML) methodology to detect and classify the existing residential urban-form typologies and their spatial characteristics within the Arc area, and (ii) to use these typologies to forecast the future likely residential typologies and the number of dwellings for both new developments and densification of existing residential areas (primarily on brownfield land). This work currently focuses on the densification of brownfield land, but future work will consider densification and development on greenfield sites.

6.1.1 Data

The following data sources has been used: (i) the GIS building layer data for the ARC is composed of 1,362,743 residential buildings; (ii) residential gardens were extracted and processed from the GIS building surface layer (source: Ordnance Survey); and (iii) street networks were extracted and processed from OpenStreetMap.

6.1.2 Method

We use a machine-learning classification method,[21] first, to classify and identify the generic building typologies in the Arc and, second, to estimate the likely typologies and number of dwellings in the surroundings of the brownfield sites which are subject to densification. More specifically, a combination of GIS spatial analysis and Random Forests (RF) machine-learning classification is used[22] to identify the variability of urban-form typologies within the existing cities in the Arc area. While GIS can be used for data processing and visualisation, the three phases of ML, namely training, testing and validating, are very useful for modelling and classification tasks.

21 Breiman, L. (2001). Random Forests. *Machine Learning* 45, 5-32.

22 Mohajeri, N. et al. (2018). A city-scale roof shape classification using machine learning for solar energy applications. *Renewable Energy* 121, 81-93.

The four most common individual building residential classes[23] namely, detached, semi-detached, terraced, and flats have already been identified. We built our model based on clusters of these four main pre-defined classes but define also four sub-classes for each main class. The sub-classes can be chosen based on: (i) their spatial location, either central, urban, suburban or rural); (ii) geometric attributes such as garden size, building footprint area and building perimeter; and (iii) spatial attributes such as building density, street density and site coverage. Examples are shown in Figure 10.

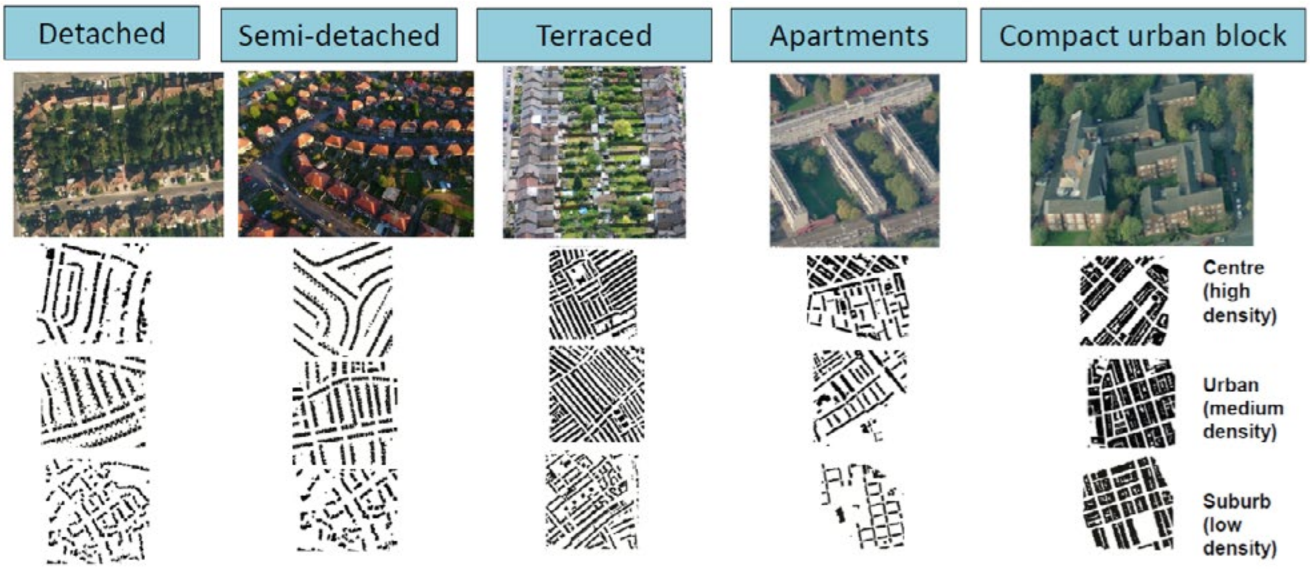


Figure 10: Example urban forms.

Define scale and attributes for classification task

Urban form may be defined as the physical structure of a city, including its shape and size, as well as spatial configuration of buildings and street networks that constitute the city.[24] Urban form, as reflected in the size and spatial distributions of buildings and street networks, affects energy-system infrastructure as well as the transport and water infrastructure of a city. We consider the relations between the urban form and infrastructure systems in our models while carefully selecting the scale and the attributes.

Scale

We choose a neighbourhood/district scale, using a grid of 500m×500m squares. The grid covers the whole area of the Arc. This scale is chosen in order to (i) isolate a single urban form, ideally consisting of a single building type (though this may not always be possible), and (ii) compute attributes that can affect the infrastructure systems.

23 Hargreaves, A.J. (2015). Representing the dwelling stock as 3D generic tiles estimated from average residential density. *Computers, Environment and Urban Systems* 54, 280–300.

24 N. Mohajeri, et al. (2016). Effects of urban compactness on solar energy potential, *Renewable Energy* 93, 469-482.

Attributes

The following attributes have been chosen in order to reflect the design parameters and their impacts on the infrastructure systems, including energy infrastructure, transport infrastructure, and water infrastructure. These include building density, site coverage (% of building footprint area), street network density, street connectivity, building dimension (perimeter, area) and garden dimension (perimeter, area).

6.2 Natural capital and green infrastructure

Natural capital is the elements of nature that directly or indirectly produce value to people, including ecosystems, species, freshwater, land, minerals, the air and oceans, as well as the natural processes and functions that link these components and sustain life.[25] Healthy stocks of natural capital underpin the delivery of essential services for human health and wellbeing. These 'ecosystem services' include provision of food, fresh water, clean air, natural flood management, carbon storage, crop pollination, green space for recreation, and opportunities for interacting with and learning from nature.

We assess natural capital using a matrix of indicative scores from 0 to 10 that reflect the ability of different habitat types to deliver 18 different ecosystem services. Multipliers can adjust these generic scores to reflect factors such as habitat condition, location or whether there is public access. The scoring system and multipliers have been developed by the University of Oxford and partners over several years, incorporating a literature review of 780 papers[26] and a series of stakeholder workshops and expert consultations as part of development of an eco-metric tool for Natural England.[27] The system is still being reviewed and refined, but it provides a useful way of producing maps and conducting initial scoping assessments of the impacts of land use change on natural capital. However, it is not a biophysical model and it does not include monetary assessment. Scores for the different services (e.g. carbon storage and recreation) cannot be added together because they are not in common units. Further information is provided in Appendix A7.

This method has been recently used to produce natural capital maps of Oxfordshire, using a base map that incorporates OS MasterMap, Oxfordshire Phase 1 Habitat and Land Use data, Agricultural Land Class, and habitat designations.[28] To extend this method to the Arc, we use Natural England Priority Habitat data, though this is less detailed and up to date than local habitat data.

25 Natural Capital Committee (2019). Natural Capital Terminology.

26 Smith, A.C. et al (2017). How natural capital delivers ecosystem services: a typology derived from a systematic review. *Ecosystem Services* 26: 111–126.

27 Smith, A.C., Baker, J., Berry, P.M., Butterworth, T., Dunford, R., Hölzinger, O., Howard, B., Norton, L.R., Sadler, J. and Scott, A. (2019). An Eco-metric approach to growing natural capital, Final report of Phases 1 and 2. Annex 2: Rationale for scores and multipliers. Report to Natural England. Not yet published but available on request.

28 Smith, A.C. (2019). Natural Capital Mapping in Oxfordshire. Draft report. Environmental Change Institute, University of Oxford. Not yet published.

To distinguish arable land from improved grassland (i.e. intensive pasture), we use the CEH Land Cover map.[29]

We apply selected multipliers to adjust the basic scores to reflect habitat condition and other factors. Agricultural Land Class is used to adjust the food production scores for farmland. Areas with nature and cultural designations (AONBs, Green Belt, Local and National Nature Reserves, SSSIs, Special Areas of Conservation, Special Protection Areas, Ramsar sites, RSPB reserves, Important Bird Areas, Ancient Woodland, Country Parks, National Trust properties and Doorstep and Millennium Greens) receive an extra multiplier to reflect their importance for cultural ecosystem services. Finally we use the OrVal parks and paths dataset (with permission from the University of Exeter) and other sources to indicate which areas are likely to have public access.

In line with the UK Government 25 Year Environment Plan,[30] local groups within the Arc are developing Nature Recovery Networks which are critical to reverse the steep decline in species abundance and diversity that is being caused by human activity.[31] It is important that new development does not prevent the establishment of these habitat networks. Our natural capital maps therefore incorporate not only existing high value natural capital assets, but also the potential future networks that link these assets and can provide corridors for wildlife as well as recreational and active travel routes for people. Our initial approach uses Natural England's Habitat Networks as well as some early drafts of the networks currently being developed by Local Nature Partnerships within the Arc.

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29 Rowland, C.S.; Morton, R.D.; Carrasco, L.; McShane, G.; O'Neil, A.W.; Wood, C.M. (2007) Land Cover Map 2015 (vector, GB). NERC Environmental Information Data Centre. https://doi.org/10.5285/6c6c9203-7333-4d96-88ab-78925e7a4e73. Dataset is FileGeoDatabase geospatial data, Scale 1:2500, Tiles: GB, Updated: 26 May 2017, CEH. Using: EDINA Environment Digimap Service, https://digimap.edina.ac.uk

30 HM Government (2018). A Green Future: Our 25 Year Plan to Improve the Environment. The Stationary Office Ltd.

31 Hayhow, D.B., Eaton, M.A., Stanbury, A.J., Burns, F., Kirby, W.B., Bailey, N., Beckmann, B., Bedford, J., Boersch-Supan, P.H., Coomber, F., Dennis, E.B., Dolman, S.J., Dunn, E., Hall, J., Harrower, C., Hatfield, J.H., Hawley, J., Haysom, K., Hughes, J., Johns, D.G., Mathews, F., McQuatters-Gollop, A., Noble, D.G., Outhwaite, C.L., Pearce-Higgins, J.W., Pescott, O.L., Powney, G.D. and Symes, N. (2019). The State of Nature 2019. The State of Nature partnership.

7. Results

7.1 Road transport

The following sections give an overview of the results from the road transport model, in terms of car traffic within LAD zones in the Arc, the impact of the new Expressway on route choices, travel times, energy consumption, emissions and congestion.

7.1.1 Zonal car traffic

Figure 11 to Figure 14 show zonal vehicle-kilometres in local authority districts (LADs) covering the Arc area. These were calculated by combining the passenger car vehicle-kilometres on major road links falling within a particular zone (simulated using a network assignment procedure) and vehicle-kilometres on minor roads falling within a particular zone (simulated by sampling from an observed trip length distribution, without an explicit network representation). Vehicle-kilometres as a measure of zonal car traffic are not only a function of travel demand but also dependent on the zone size and road network density in that particular zone. It is therefore not surprising that smaller zones, such as the ones representing the cities of Oxford and Cambridge, have relatively smaller values of total vehicle-kilometres compared to the bigger zones. Nonetheless, this measure is still useful to assess the differences in zonal car traffic across various population scenarios. Figure 12 for 'Unplanned Development' shows some increase in total vehicle-kilometres in the zones along the new Arc transport infrastructure. The 'New Settlements' and 'Expansion' scenarios result in bigger increases in vehicle-kilometres, especially in the zones expected to have more significant population growth and therefore more travel demand.

7.1.2 Route choice and travel times

The network assignment procedure is based on a discrete-choice model (the path-size logit). This route-choice model is applied for each vehicle trip from the origin-destination matrix to determine the route between origin and destination nodes, taking into account variables such as travel time, distance and cost. For each pair of nodes (representing road intersections) there are up to five route alternatives and the route with the highest utility has the highest probability of being selected. These route-sets are pre-generated using a routing algorithm and a random link elimination method, resulting in more than 90 million route alternatives for the whole of Great Britain. This off-line route-set generation enables faster network assignment as it is not necessary to use computationally expensive routing algorithms during model runs.

In 2030, the model dynamically creates new road links corresponding to the chosen route option and inserts them into the existing road network. This means that the pre-generated route-set needs to be expanded with new route alternatives. This is achieved by triggering the route generation procedure for a subset of the origin-destination matrix where both trip origin and trip destination zone fall within the Arc.

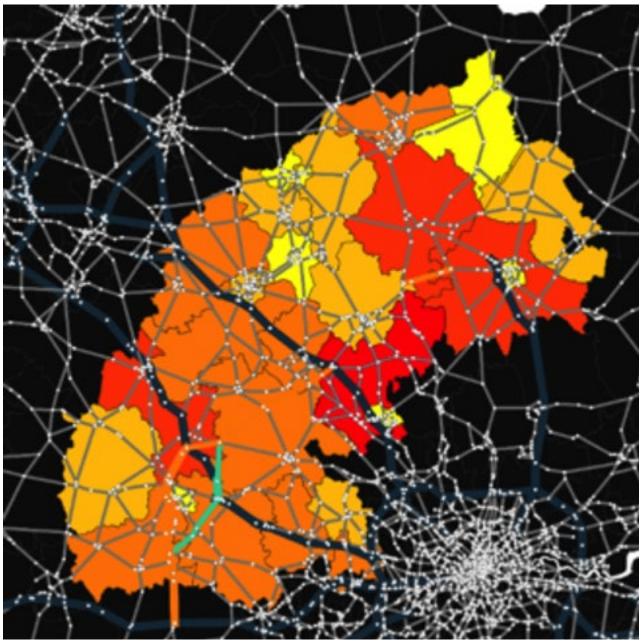


Figure 11: Vehicle-kilometres in Arc zones (Baseline, 2050).

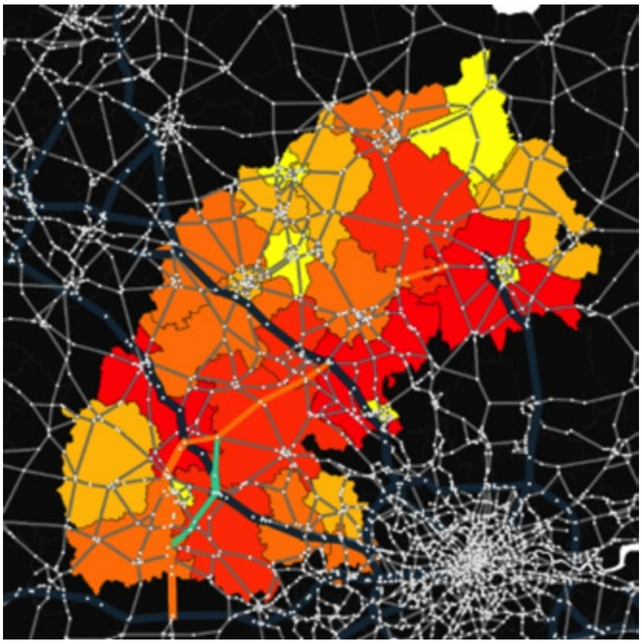


Figure 12: Vehicle-kilometres in Arc zones (Unplanned, 2050).

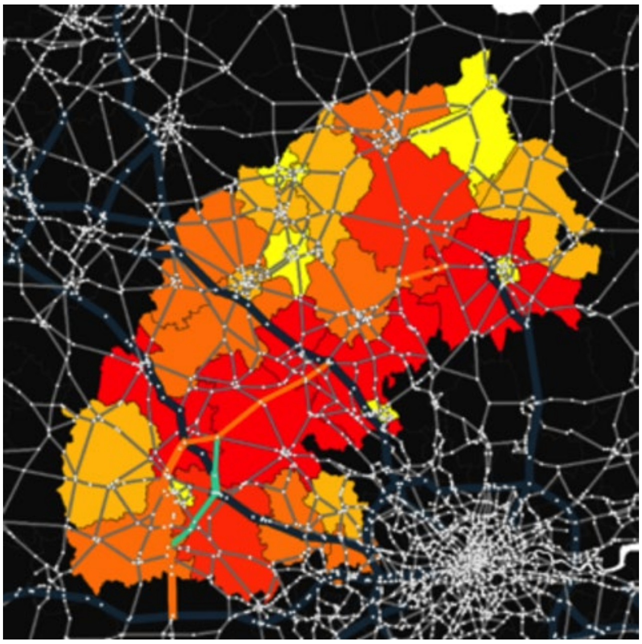


Figure 13: Vehicle-kilometres in Arc zones (New Settlements, 2050).

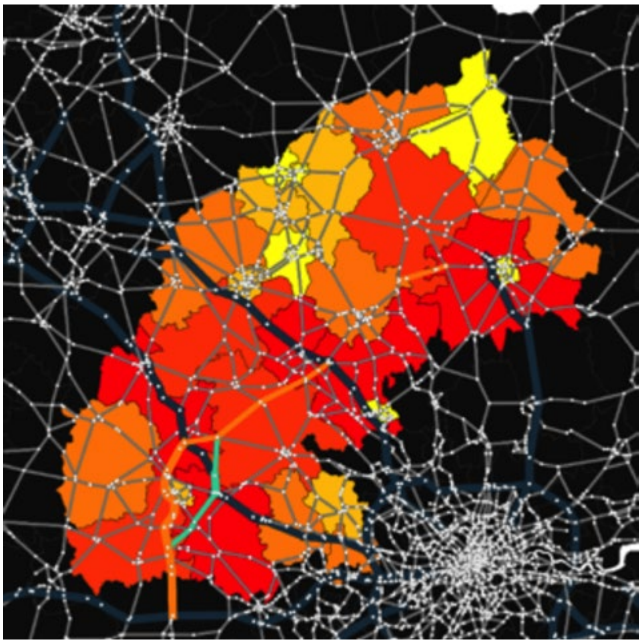


Figure 14: Vehicle-kilometres in Arc zones (Expansion, 2050).

Annual million vehicle km (2050)
(UK total 400 billion vehicle km)

- 300 - 1000
- 1000 - 1700
- 1700 - 2400
- 2400 - 3100
- 3100 - 7000

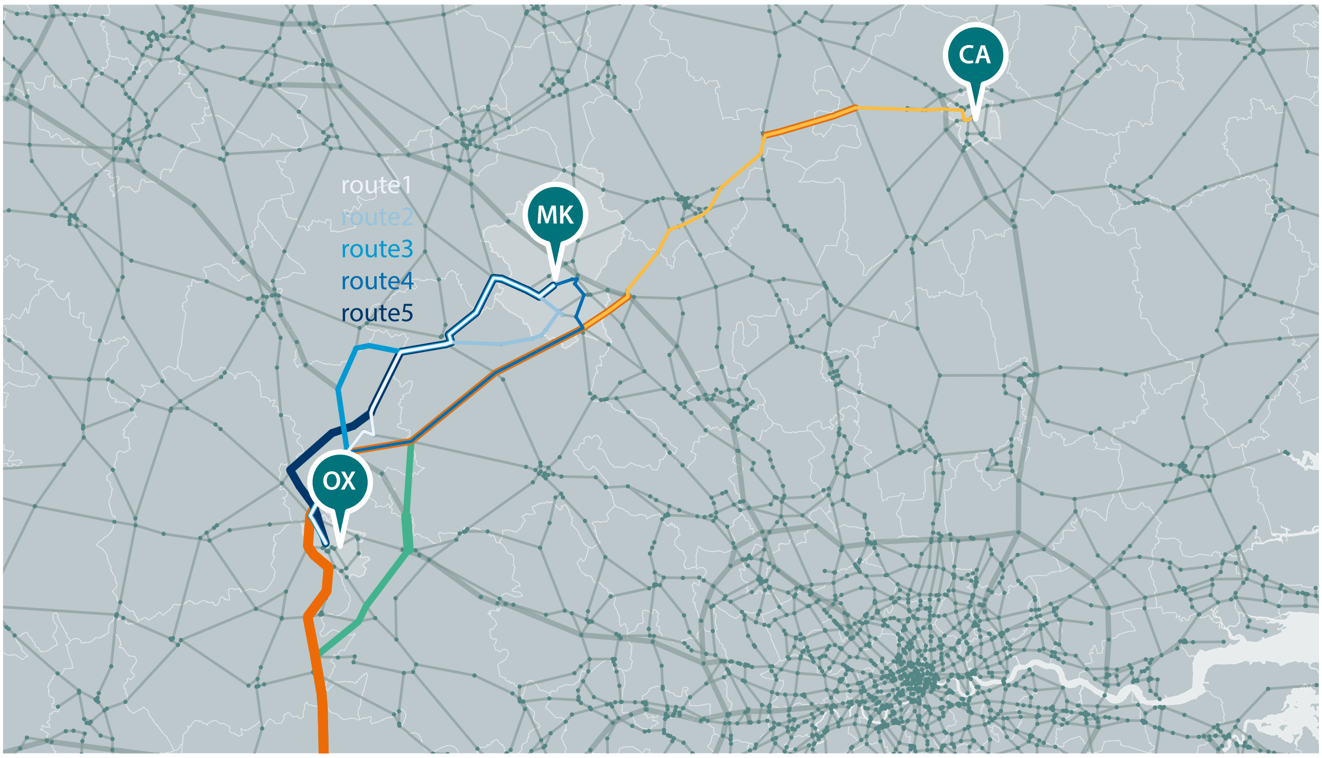


Figure 15: Route sets for fastest trips between the centres of Milton Keynes and Oxford (blue) and Cambridge and Oxford (yellow).

The analysis of routes generated in year 2030 between the centre of Milton Keynes and the centre of Oxford shows that the fastest route is not making use of the newly built road through Winslow, but the existing roads north of the proposed corridor. In fact, among the five route alternatives generated for this trip, only one of them makes use of the new links which form the expressway. This suggests that the new road is not as competitive a route option for travelling between the city centres of Milton Keynes and Oxford as might initially have been expected (see Figure 15). Furthermore, an assumption was made that new road links are almost straight lines with minimal curvature. In practice this may not be the case as other considerations, such as the preservation of natural habitat, might require new roads to meander more, which would increase their total length and render them even less competitive.

On the other hand, the optimal route between Cambridge and Oxford clearly did use the newly developed link, suggesting that the fastest route option would in future go south of Milton Keynes. It can be expected that avoiding the centre of Milton Keynes will lead to significant time savings for that trip.

The cities of Oxford, Milton Keynes and Cambridge can hardly be considered commutable from each other at present, and our estimated base-year origin-destination matrix also shows no substantive car travel between them. Nonetheless, it is still interesting to study changes in intercity travel times to understand how (and if) the provision of new road infrastructure might facilitate travel along the Arc.

Figure 16: Intercity travel times (route B1, 2030).

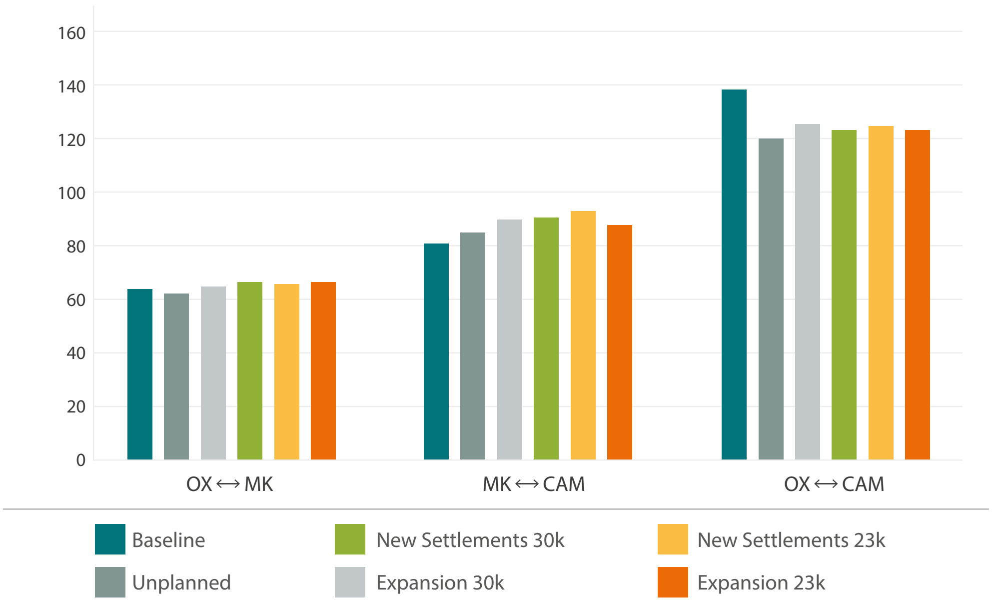
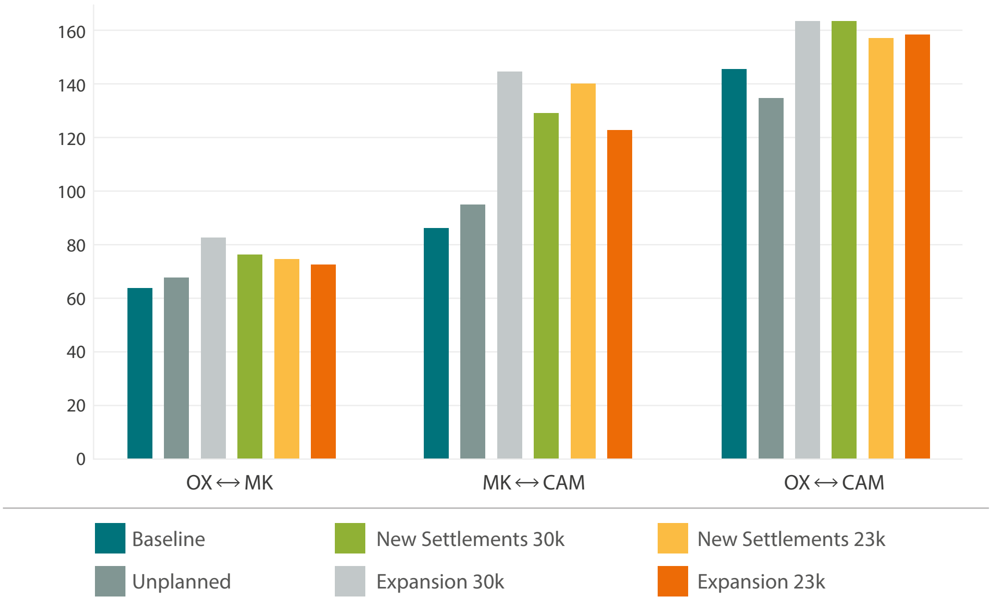


Figure 17: Intercity travel times (route B1, 2050).



The analysis of average intercity travel times (between the city centres of Oxford, Milton Keynes and Cambridge) captures the interplay between travel demand and road infrastructure. While an increase in population and travel demand is expected to increase road congestion thereby also increasing travel times, the provision of new road infrastructure (e.g. expansion with new lanes or development of new road links) is expected to alleviate congestion and improve travel times (or at least postpone their increase with an ever-increasing demand).

We assume that in 2030 the route option B1, consisting of new road links through Winslow and several road expansions, will be implemented. Figure 16 shows that not much change in travel times between Milton Keynes and Oxford should be expected, despite the new road. Travel times between Cambridge and Milton Keynes increase somewhat with the increase in population, suggesting that dualling of the section of A428 will not suffice to maintain base year travel times.

However, a substantial reduction in travel times can be observed between Oxford and Cambridge (15-20 minutes compared to the Baseline scenario), where it seems the new road will be most beneficial.

By 2050, the population increase included in various population scenarios will result in increased travel times, regardless of the new infrastructure built in 2030 (the only exception being the travel time between Oxford and Cambridge under the 'Unplanned Development' scenario, see Figure 17). This suggests that under high-growth scenarios more new infrastructure will need to be provided if it is deemed necessary to maintain road travel times at their current levels.

In summary, our strategic road transport model demonstrates that the Expressway provides a new fastest route between Oxford and Cambridge, as traffic no longer has to negotiate roads in and around Milton Keynes. Travel times are reduced by 15-20 minutes compared with Baseline journeys. However, for journeys between central Milton Keynes and Oxford, there are several existing routes which provide similar or faster travel times in uncongested conditions. Locally, the new road link will for example be beneficial to the inhabitants of Winslow (or any new settlements built in that area), for reducing their drive times to Oxford or Milton Keynes.

7.1.3 Electricity consumption

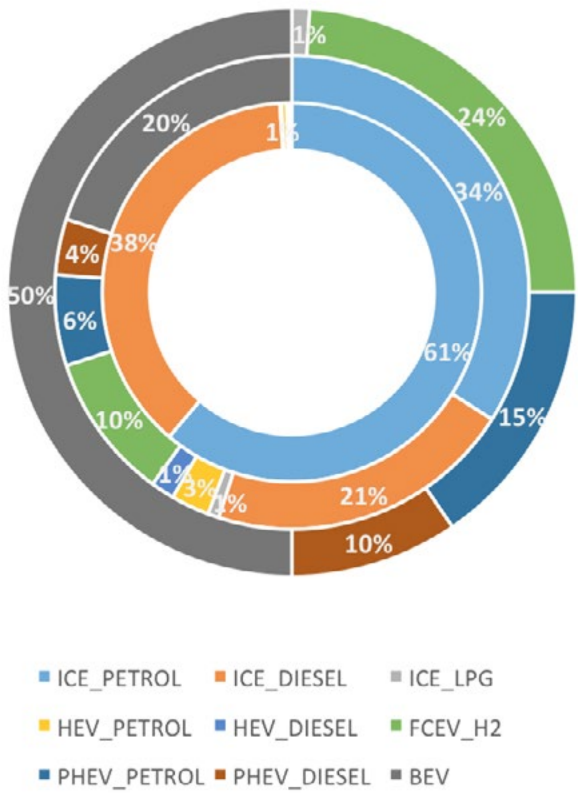
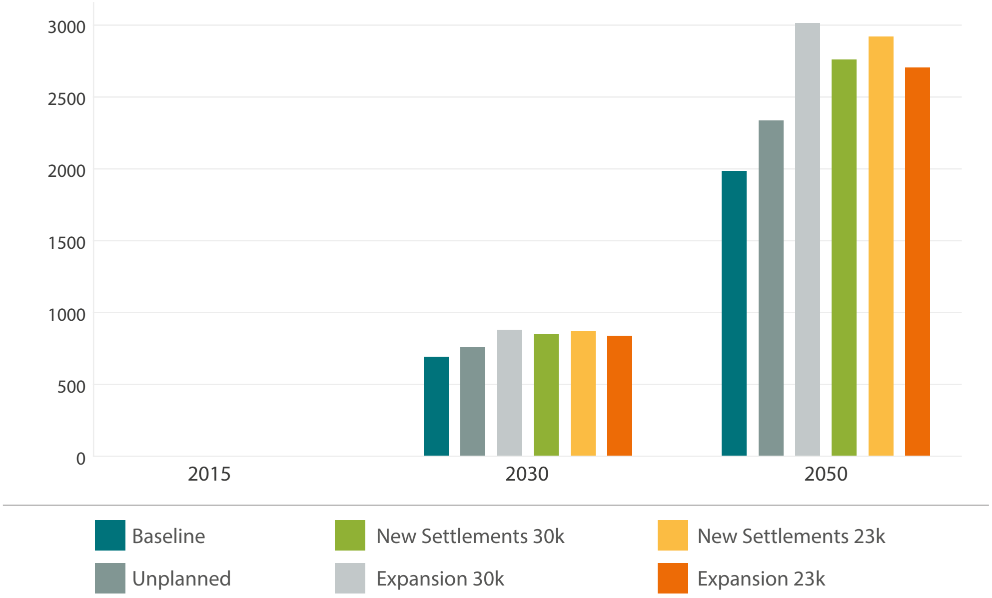


Figure 18 shows an assumed vehicle electrification scenario for the analysis described here. The market share of electric cars (battery-electric and plug-in hybrid) is assumed to grow from negligible in 2015 to 30% in 2030 and 75% in 2050.

Figure 19 shows yearly electricity consumption of car trips within the Arc area. The consumption increases markedly from 2015 to 2030, and then increases 3-4 times from 2030 to 2050. This growth in electricity demand will need to be served by the energy sector, which is one of the main cross-sectoral interdependencies that needs to be better understood, and is discussed in Section 7.2.1.

Figure 18: Vehicle electrification scenario with market shares of passenger car engine types (inside: 2015, middle: 2030, outside: 2050).

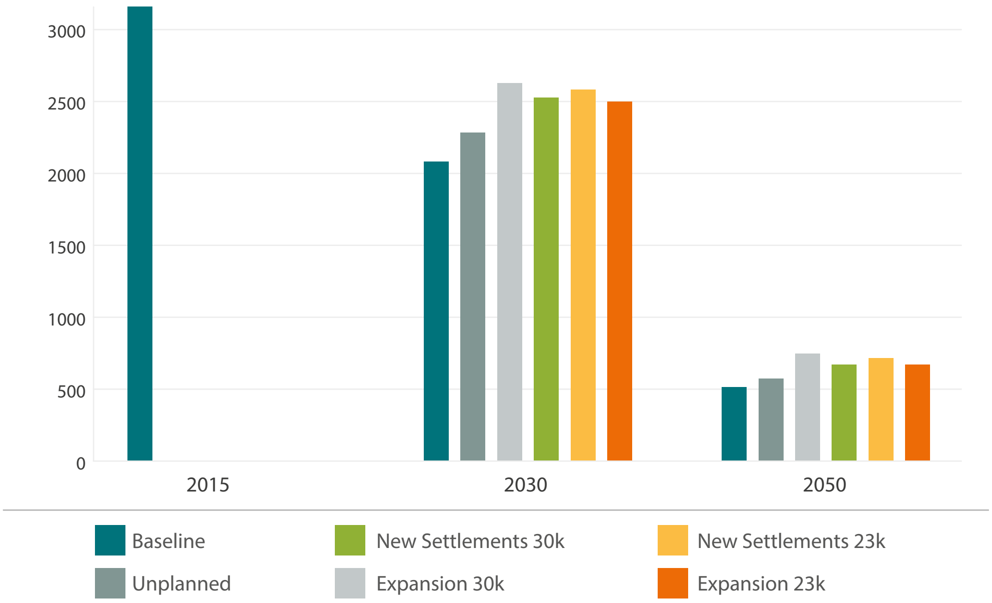
Figure 19: Yearly electricity consumption for car trips within the Arc.



7.1.4 CO_2 emissions

Total yearly CO_2 emissions for car trips in the Arc (Figure 20) have been calculated from the carbon content of consumed petrol, diesel and gas. For zonal maps (Figure 21 to Figure 26), CO_2 emissions of each trip have been split 50%-50% between the trip origin and trip destination zone. Figure 20 shows that, despite the population growth, a substantial decline in CO_2 emissions can be expected as a direct result of the vehicle electrification. In 2050, total CO_2 emission is expected to drop to about 20% of the base-year emission. Figures 19-21 show zonal distribution of CO_2 emission for the Baseline scenario in 2015, 2030 and 2050. Spatial analysis across the scenarios (Figure 24 to Figure 26) suggests that in 2050 there will be more CO_2 emissions in zones along the Arc corridor than elsewhere in the region, consistent with the population projections.

Figure 20: Yearly CO_2 emission for car trips in the Arc.



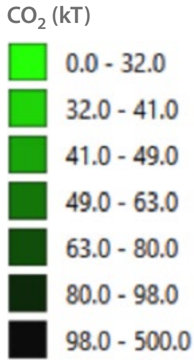


Figure 21: CO_2 emissions in Arc zones (Baseline, 2015).

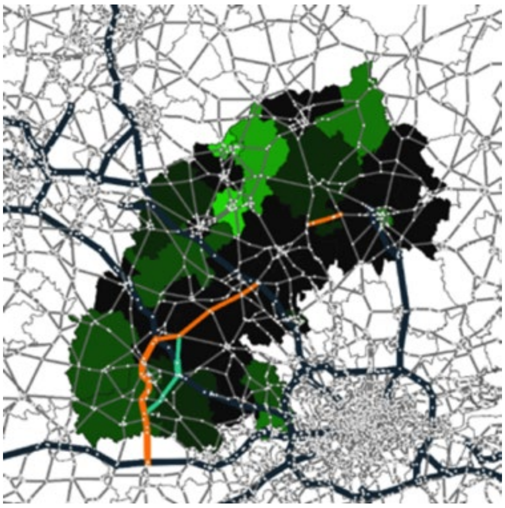


Figure 22: CO_2 emissions in Arc zones (Baseline, 2030).

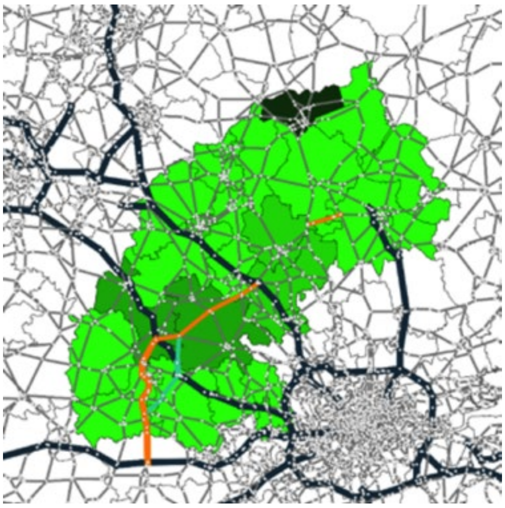


Figure 23: CO_2 emissions in Arc zones (Baseline, 2050).

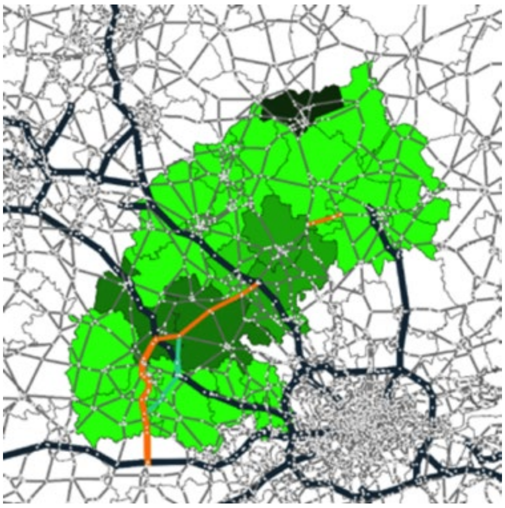


Figure 24: CO_2 emissions in Arc zones (Unplanned, 2050).

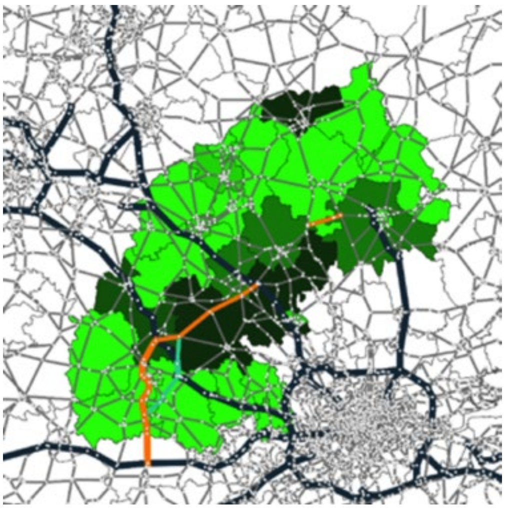


Figure 25: CO_2 emissions in Arc zones (New Settlements, 2050).

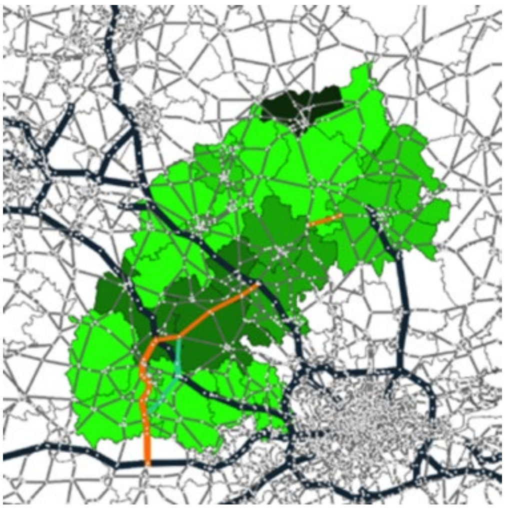


Figure 26: CO_2 emissions in Arc zones (Expansion, 2050).

7.1.5 Congestion (Capacity Utilisation)

Congestion analysis provides estimates of capacity utilisation of the major road network (A-roads and motorways). Many congested areas are evident in 2050, especially in London and on radial links that lead into London. However, some problem areas exist within the Arc as well. This situation is further exacerbated in scenarios that carry larger population increases.

Road expansion interventions on A428 (between Cambridge and Milton Keynes, and around Oxford in B1 variant) are initially somewhat helpful for reducing the road capacity utilisation, but not sufficient to deal with demand from the major population increases that are expected in 2050.

7.1.6 Transport summary

High population growth in the Arc area would put pressure on the existing road infrastructure, increasing congestion levels and travel times. This will be somewhat relieved by the provision of new 'Expressway' infrastructure, but high population increases will soon require further interventions to address the capacity pinch points, probably centred on demand management and mode shift to alternative forms of transport.

Our analysis suggests that the new road link through Winslow will mostly be useful for reducing travel times between Cambridge and Oxford. It is also likely to be beneficial to the inhabitants of Winslow (or any new settlements built in that area), by reducing their commute time to Oxford or Milton Keynes. This, however, we cannot demonstrate with our model due to its limitations and assumptions.

Despite the overall increase in population and car traffic, the environmental footprint of road use will substantially improve due to trends and policies of vehicle electrification. This will also result in considerably increased electricity demand in the area, as discussed in Section 7.2.1.

7.2 Energy

Meeting the net zero carbon emissions target by 2050 is likely to require a power system that is largely decarbonised and heat related emissions from buildings substantially reduced. These are formidable objectives and will require laying the foundations for these emission reductions by the late 2020s.

Planning and preparation for decarbonising the energy system needs to commence in order to pave the way for emission reductions in a cost-effective manner whilst meeting end user requirements. National energy system decisions and polices have a direct impact on the options available locally. As an example, the rate of decarbonisation of the national power system influences the carbon emissions footprint of energy consumed locally.

NISMOD's energy systems model has been used to assess the how different strategies for energy supply, from zero carbon electricity to use of 'green' gases or local heat networks, could affordably reduce or eliminate carbon emissions from the Arc's energy system. A summary of these strategies is illustrated in Table 3.

The following outputs illustrate key energy supply systems metrics – energy demand, energy supply, emissions and costs focusing on the Arc region across scenarios and heat supply strategies.

Table 3: Summary of heat supply system strategies (2050)

	Energy strategy			
	Electric	Heat networks	Green gas	Unconstrained*
Heat supply	Heat supply driven completely by electricity: Heat pumps, resistive heating and electric boilers.	Heat supply is mainly from Combined Heat and Power (CHP) units utilising natural gas, biomass and solid waste. Availability of biomass and solid waste is restricted. Gas boilers are used to back-up CHP units during peak periods.	Use of dedicated hydrogen boilers for heating. Gas boilers remain to produce heat (as green gas is injected into the gas mix). Biomass/Biogas CHP units are installed.	Full availability of technologies. Availability of resources such as biomass and waste is restricted.
Electricity supply	Distributed wind and solar photovoltaic (PV). CHP units are installed as they produce heat (Heat driven CHP operation) and power. Backup gas-fired generators.			
Gas supply	Transmission grid supplies are available with limited gas storage facilities within the region.		Hydrogen and biogas injection into the gas grid limited to 20% by volume. Large scale hydrogen production via Steam Methane Reforming (SMR) Carbon Capture and Storage (CCS), and small-scale electrolysis deployments. Hydrogen is supplied via new hydrogen pipelines and re-purposed gas distribution pipes. Anaerobic digestion plants are used to produce biogas.	Transmission grid supplies are available with limited gas storage facilities within the region.

* The optimisation model is free to select the appropriate set of heat technologies to meet demand at lowest operational costs whilst adhering to physical constraints.

7.2.1 Energy demand

The energy demands within the Arc region for 2050 across different heating strategies are shown in Figure 27. The stacked bar chart shows the energy demand composition for the Baseline scenario in 2050. The total energy demands for the other Arc scenarios are indicated by hyphens.

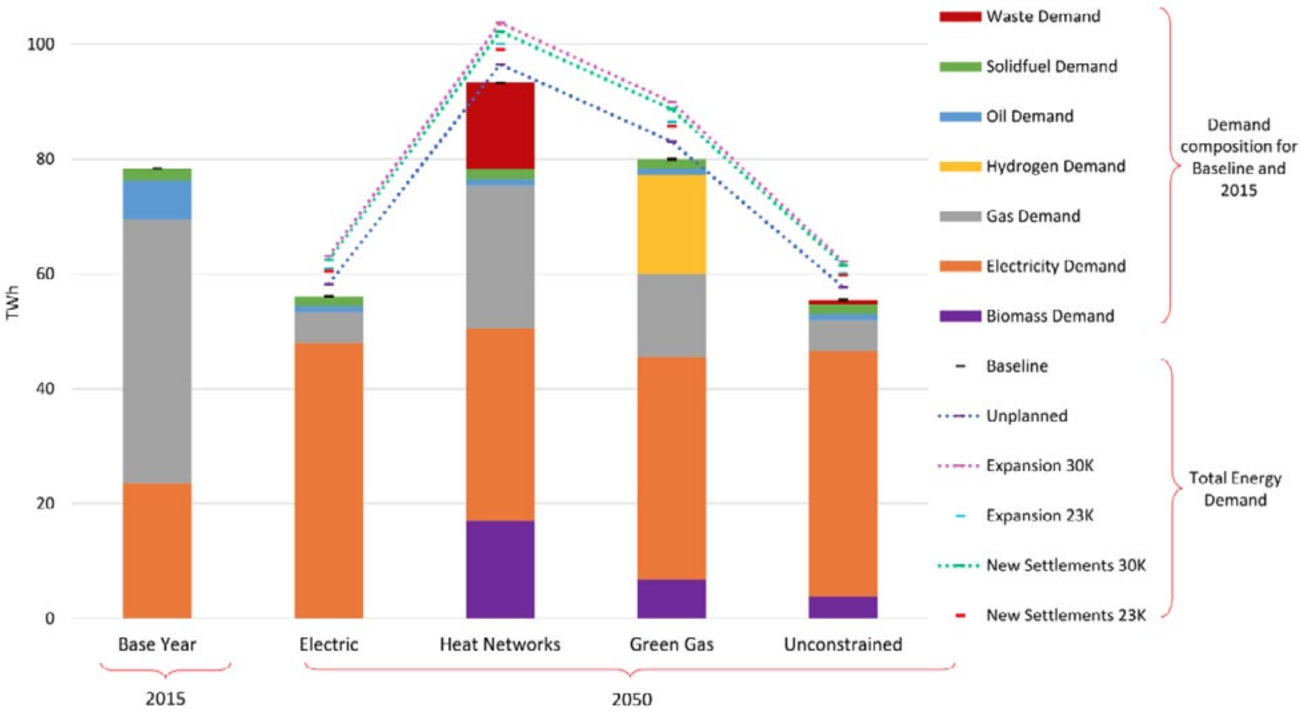


Figure 27: Annual energy demand comparison between 2015 and across heating strategies in 2050.

Among the Arc scenarios, 'Expansion 30k' and 'New Settlements 30k' show the highest final energy demand in line with projected population growth by 2050. There is a difference of approximately 10TWh between the Expansion (highest demand) and Baseline (lowest demand) scenarios for final energy demand. The final energy demand mix; gas/electricity/hydrogen/biomass/waste/solid fuel across all Arc scenarios was found to be similar to Baseline as shown in Table 4.

Within the industrial sector in 2050, both oil and solid fuel demands are approximately ~1.2TWh each. By 2050, annual oil demand has decreased by 5.6TWh, and solid fuel by 0.8TWh compared to 2015. This is due to substitution by other fuels and through overall demand reduction due to improved efficiencies.

Most of the gas demand (~80%) in 2015 was used for heating in gas boilers. Therefore, the choice of heating strategy greatly influences the annual energy demand mix in 2050. The heat strategies presented, essentially replace gas demand for heating with alternatives such as electricity, hydrogen, biomass and solid waste.

Table 4: Energy demand mix in 2050 for the Baseline scenario							
Heat Strategy	Share of final energy demand by fuel (%)						
	Biomass	Electricity	Natural Gas	Hydrogen	Oil	Solid Fuel	Waste
Base Year (2015)	0.1	29.9	58.6	0.0	8.8	2.6	0.0
Electric	0.0	85.5	9.5	0.0	2.0	3.0	0.0
Heat Networks	18.2	35.9	26.7	0.0	1.2	1.8	16.2
Green Gas	8.5	48.5	18.0	21.5	1.4	2.1	0.0
Unconstrained	6.8	77.3	9.6	0.0	2.1	3.0	1.2

In electric and unconstrained heating strategies, a large amount of electricity is used for heating via heat pumps. Due to greater heat pump efficiencies and better insulated homes, the electricity demand required for heating is significantly lower and therefore approximately ~20TWh less annual energy demand is required compared with 2015 (this is despite an increase in population and number of dwellings by 2050 within the Arc region). In contrast, less efficient production of heat from hydrogen, biomass and solid waste in the green gas and district heating strategies results in final energy demand being higher than in 2015 in almost all the scenarios. Whereas on a per capita household basis energy demands in 2050 across all scenarios and heating strategies are far lower than in 2015 as shown in Figure 28.

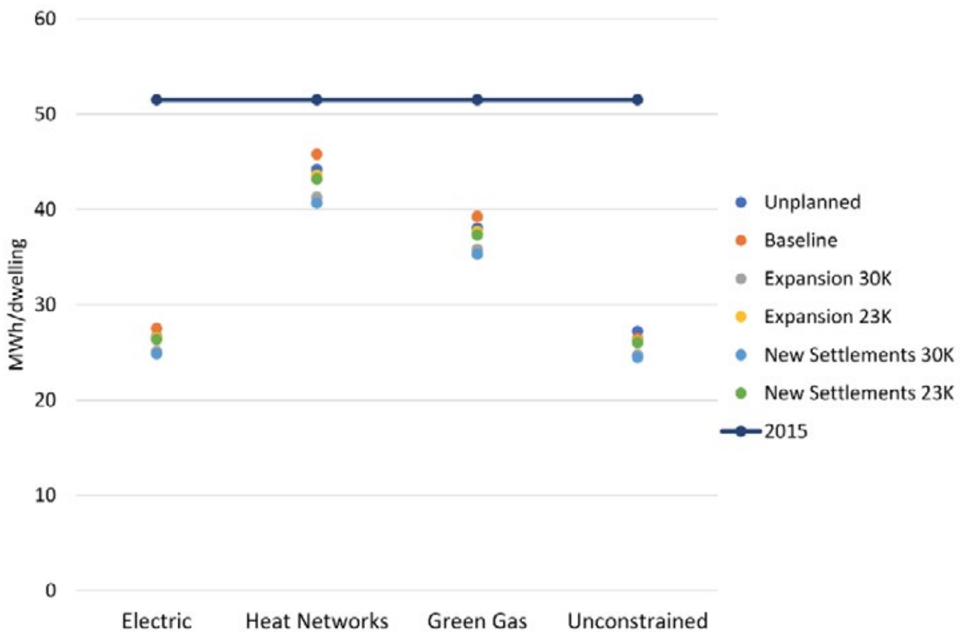


Figure 28: Energy demand per capita (households) across Arc scenarios and strategies in 2050.

The results yield on average, dwellings consuming less energy due to efficiency improvements in homes and heating technologies at building level in 2050 compared with 2015.

7.2.1.1 Electricity demand

Electricity demand calculations for the Arc region in 2050 (includes demand for heating, hydrogen production and transportation) are shown in Figure 29.

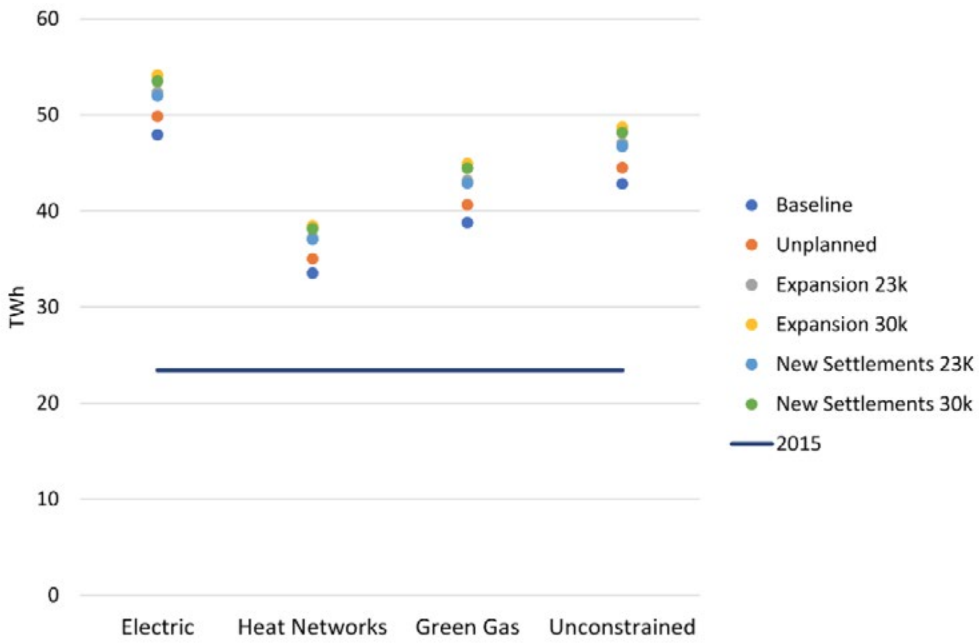


Figure 29: Annual electricity demand in 2050 (including demand for heating and transport).

Electricity demand within the Arc region in 2050 is greater than in 2015 in all scenarios. In 2050, electricity share of final energy demand accounts for as low as 36% in the district heating strategy and as high as 86% in the 'electric' heating strategy (Table 4). The New Settlements and Expansion 30k scenarios show the highest additional growth of approximately 30TWh annual electricity demand in 2050 from 2015 levels where almost half, ~14.7TWh is due to electric vehicle (EV) charging demand. Across the scenario space, Baseline electrical demand grows the least due to lower population growth and dwellings compared to the Expansion and New Settlements scenarios. These changes in growth in electricity demand are reflected across all the heat strategies.

Among the heat strategies 'electric' has the highest electricity demand in 2050 with majority of the demand due to the use of heat pumps. Electrification of the heating sector varies in the other heat strategies. This is reflective of the heat strategy chosen and the prominence given to other vectors such as gas, hydrogen and deployment of district heating systems.

The growth of EVs is projected to be in line with the growth in population across the Arc scenarios. Similar growth patterns are projected across the New Settlements and Expansion scenarios for both 23k and 30k growth variants, recording the highest annual charging demand of 14.7TWh as shown in Figure 30. There is only 1TWh difference between the highest (New Settlements 30k) and lowest annual EV charging demand (Baseline) in 2050.

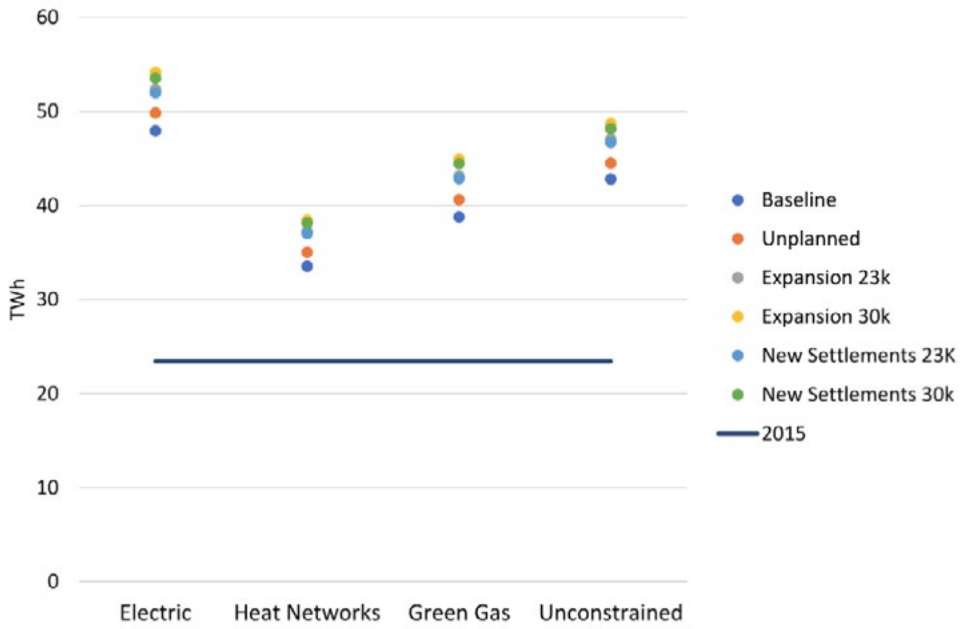


Figure 30: Annual electricity demand for charging electric vehicles across the Arc scenarios.

7.2.1.2 Gas demand

Annual demand for natural gas drops significantly across the Arc scenario space by 2050, to less than half of that in 2015 (~45TWh). In almost all electricity-based heating strategies in 2050 (electric and unconstrained) the gas demand declines even further to 5TWh/year (90% lower). As natural gas has no significant role in these electric heating strategies, the variation in population and dwellings across the Arc scenarios has little or no impact on the gas demand (clustered points in Figure 31). Whereas in district heating and green gas heating strategies, the variation of gas demand across Arc scenarios are greater (2TWh between Baseline and Expansion 30k in the district heating strategy). This is due to the production of heat via Combined Heat and Power (CHP) units and hydrogen using natural gas which follows demand emanating from population and dwelling differences across the scenarios.

The use of natural gas is highest (~12TWh) in district heating strategies in 2050 as it is mainly used to produce heat via district heating gas CHP units. In the green gas heating strategy natural gas demand declines to 8TWh as biomethane (5TWh) and hydrogen (1.1TWh) are blended (20% by volume injection) into the gas network. Hydrogen blending within the gas network is limited by regulatory issues, thus growth in biomethane has the potential to further replace the use of natural gas in the energy mix.

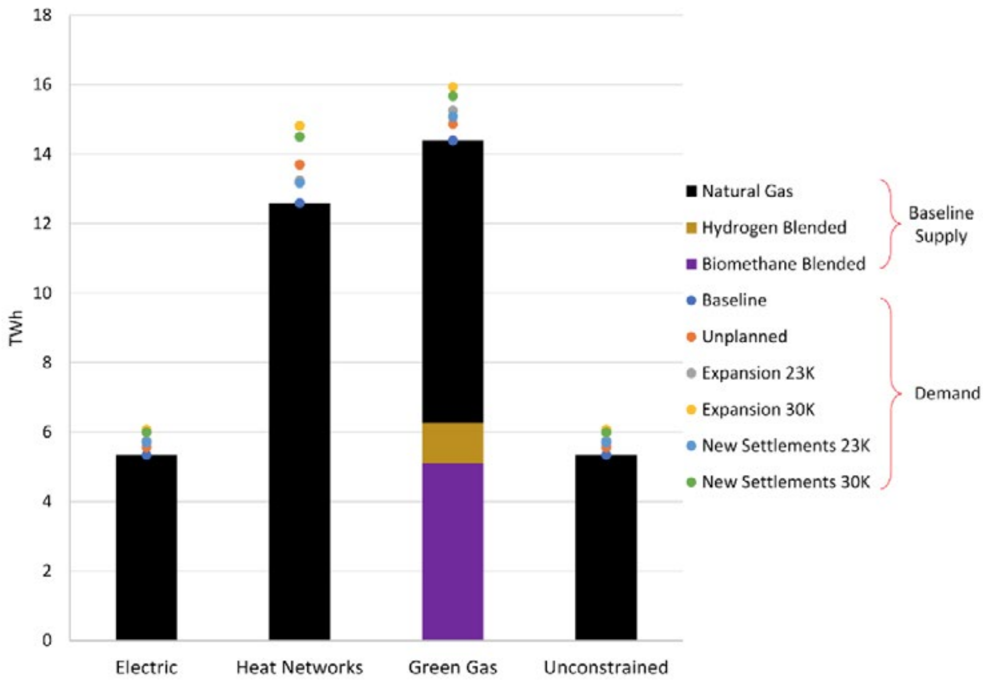


Figure 31: Annual gas demand in 2050 across heating strategies.

7.2.1.3 Hydrogen and biogas demand

Hydrogen is produced primarily from Steam Methane Reformation (SMR) with carbon capture and storage (CCS) and small volumes by electrolysis. The annual demand for hydrogen within the region for green gas heating strategies by 2050 is 18TWh in the Expansion 30k scenario (highest) and 17TWh in the Baseline scenario (lowest), from which 7-8% is the hydrogen volume injected into the existing gas network to blend with natural gas. Hydrogen demand is mainly for heating and high temperature industrial applications.

As the natural gas demand drops from 45TWh (2015) to an average of 10TWh (2050) across all scenarios, approximately 40% of the existing gas network is required to transport natural gas and the hydrogen/biogas mixture. The reminder of the gas network is re-purposed to transport hydrogen (green gas strategy). Any additional hydrogen requirements are transported via newly built dedicated hydrogen pipelines.

Biogas injected into the gas network averages 5TWh across all scenarios for the green gas strategy.

7.2.2 Energy supply

7.2.2.1 Heat demand and supply

The variation in annual heating demand across Arc scenarios is shown in Figure 32. The overall demand for heating is projected to decline by 2050 across all scenarios due to ambitious 25% savings from improved insulation,[32] thermal comfort in the building stock and a 100% smart meter rollout[33] across the region.[34] In line with the population and dwelling variations, the Expansion 30k scenario has the highest heating demand at ~30TWh which is an additional 4TWh of demand compared to the Baseline scenario.

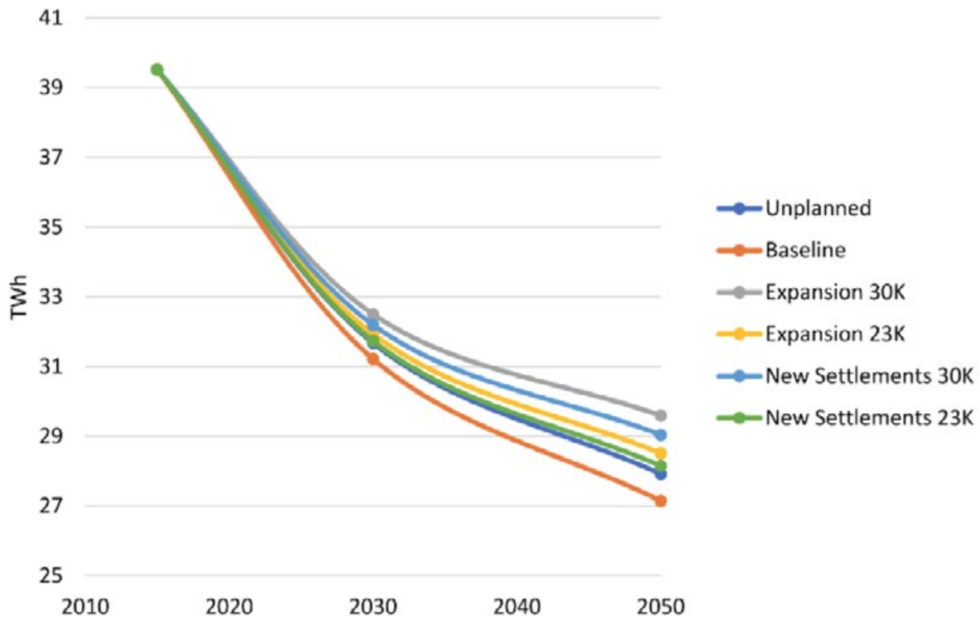


Figure 32: Variation of annual heating demand across Arc scenarios.

The heat supply strategy options illustrate multiple ways of meeting the demand for heating in 2050 across the Arc scenarios. The heat supply mix for the Expansion 30k scenario in 2050 compared with 2015 is shown in Figure 33. A similar heat supply mix is seen across the other Arc scenarios.

In the 'electric' strategy across scenarios, heat pumps (mainly air source heat pumps) are deployed throughout the region and account for 75% (including hybrid heat pumps) of the total heating demand by 2050. The highest deployment rates are found in the 30k Arc scenarios. The rest of the demand is met by resistive heating and electric boilers (mostly used for hot water). Within this strategy all dwellings are expected to be equipped with heat pumps and/or resistive heating towards 2050.

32 Savings are applied across residential, commercial and industrial sectors.

33 A 100% smart meter rollout is parameterised. This reduces final heating demand in residential, commercial and industrial sectors by approximately 3%.

34 Eggimann, S., Hall, J. W. and Eyre, N. (2019). A high-resolution spatio-temporal energy demand simulation to explore the potential of heating demand side management with large-scale heat pump diffusion. *Applied Energy*, 236(June 2018), 997–1010.

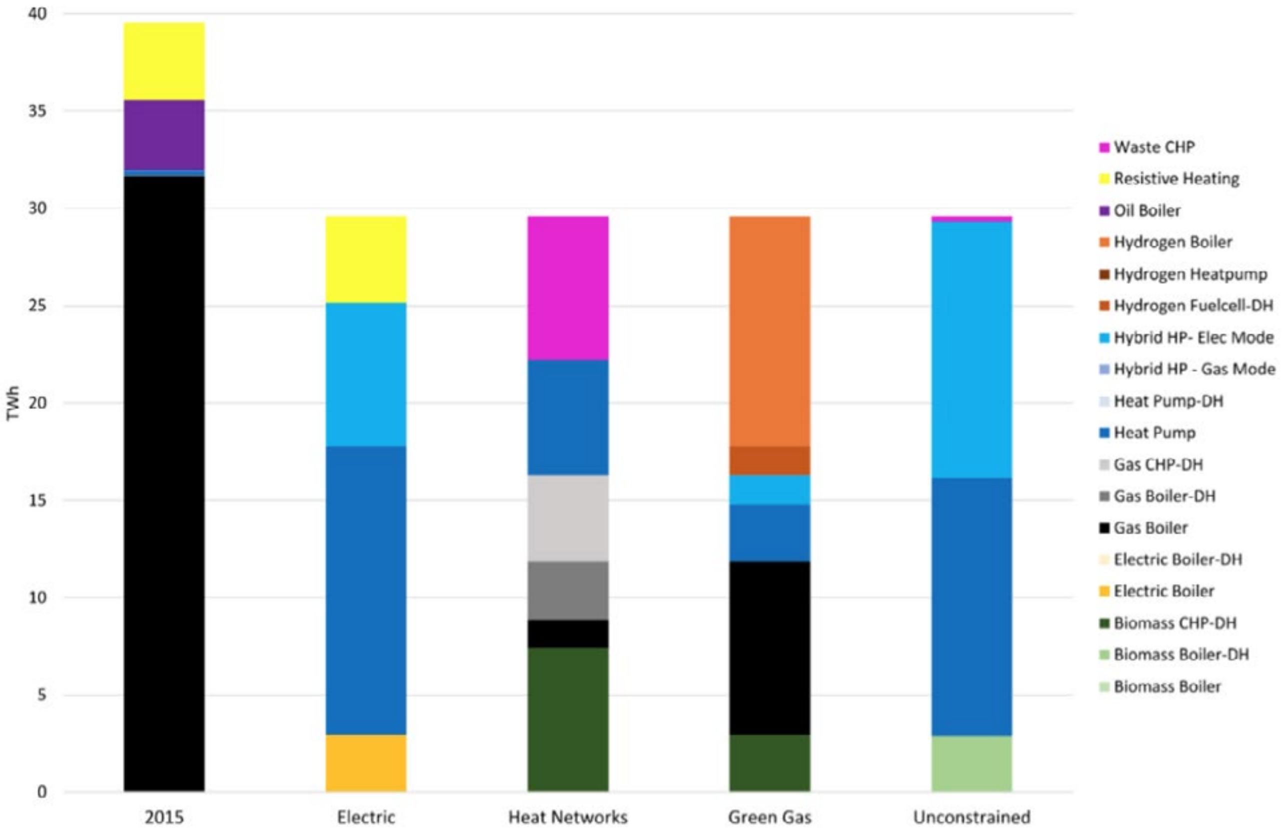


Figure 33: Annual heat supply mix in 2050 for the Expansion 30k scenario compared with 2015.

The heat networks strategy across the scenario space illustrates the utilisation of CHP units connected to district heating systems. The CHP units use mainly biomass, natural gas and waste to energy (municipal waste gasification to produce syngas for use in CHP units) under high overall efficiencies. In this strategy, biomass and municipal waste are available in local stocks and supplied regionally. The CHP units are backed up by gas boilers. On average, by 2050 in the heat network strategy across the scenarios, district heating networks supply ~70% of the total heating demand within the Arc region. The remainder of heating demand from dwellings that are not connected to the heat network are provided by a combination of gas boilers and heat pumps.

Partial decarbonisation of the gas grid takes place with the injection of hydrogen and biomethane within the green gas strategy. Therefore, across scenarios the use of building level gas boilers continues to meet 30% of the heating demand by 2050. As hydrogen production continues to grow with new infrastructure (pipelines) support, building level hydrogen boilers are deployed across the region to replace gas boilers. In green gas strategy, a combination of building level technologies – hydrogen boilers, heat pumps systems and gas boilers provide 85% of the annual heat supply. The availability of biomass and large-scale hydrogen production has encouraged the use of district heat connected technologies – biomass boilers and fuel cells for the remaining 15% of heat supply.

In the unconstrained heat strategy, full availability of different heating technologies is provided to the model. The technologies are chosen by accounting for operating and fuel costs and overall emissions. As electricity production becomes predominately low carbon (both nationally and regionally), the use of electric heating technologies is favoured. In 2050, heat pumps and hybrid heat pumps account for almost 90% of the heating demand. Further use of electricity driven technologies is limited due to network capacity of the power system (distribution and transmission to distribution capacity) and high electricity supply costs from the transmission network especially during peak hours. The remaining 10% of the heating demand is therefore met by biomass and waste to energy heating systems due to lower carbon emissions and operational costs compared with natural gas fuelled heating technologies.

7.2.2.2 Power generation

The total electricity generation within the Arc region follows the variations of the electricity demand. The generation mix of the Expansion 30k scenario in 2050 is shown in Figure 34.

Between Arc scenarios, the types of technologies and their share of final electricity supply is similar. Distributed generation and grid electricity supply from the transmission network changes in magnitude in an almost linear manner to meet variations in electricity demand across the Arc scenarios. Variations to this only become significant across heating strategies as shown in Figure 34.

In all scenarios and strategies by 2050, Vehicle-to-Grid (V2G) performs a prominent role in the local generation mix. It was assumed that a battery electric vehicle (BEV) has a 30kWh battery pack and once the vehicle is stationary, 20% of the unused battery capacity is available to provide V2G services at a power output of 7kW.[35] Given the number of EVs in 2050 (produced by EV trips from the transport model), this would represent around 2.5GW of battery storage in the Expansion 30k and New Settlements 30k scenarios (other scenarios average around 2GW). According to Figure 34, V2G accounts for upwards of at least 20% of overall local generation by 2050.

V2G services are made available within residential and commercial sectors. With the continuous growth of EV uptake by 2050, V2X (V2G and V2H (vehicle-to-home)) services become more commercially attractive than further investment in non-renewable distributed generation,[36] especially within new development regions. Within the Arc region, this becomes a prominent option in dense areas with many EVs, for example in the Expansion 30k scenario.

The available local wind and PV generators supply electricity to their maximum capacities (as long as the resource is available – wind and sunlight). No curtailment occurs in any of the scenarios regardless of the heat supply strategy chosen.

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35 Imperial College (2019). Accelerated electrification and the GB electricity system.

36 Payne, G. and Cox, C. (2019). Understanding the True Value of V2G.

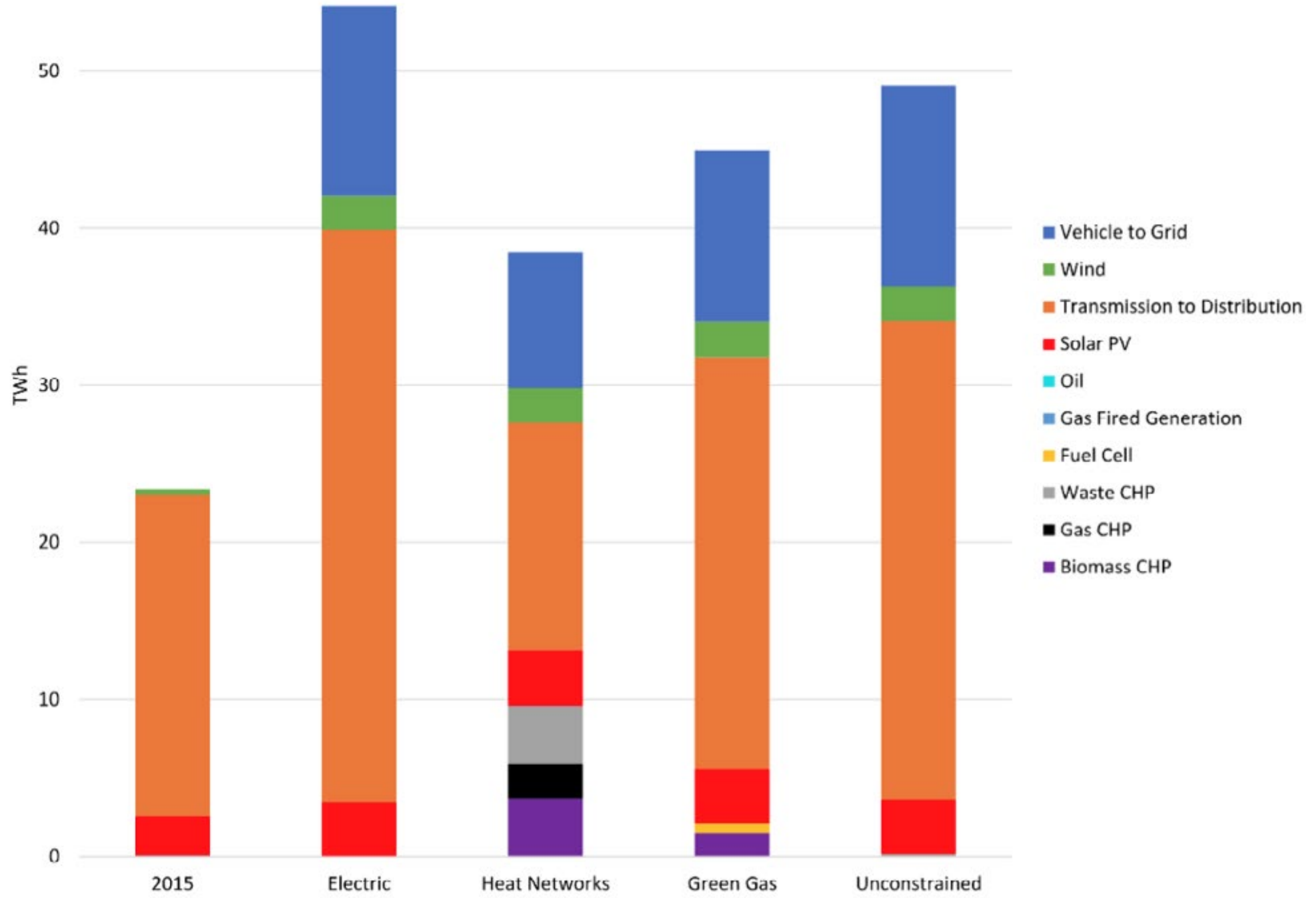


Figure 34: Electricity supply mix of the Expansion 30k scenario in 2050 compared with 2015.

The use of CHP units in the district heating strategy contributes to the local electricity supply mix up to their maximum capacities. Consequently, there is a significant decline in grid electricity imports from the transmission network into the Arc region. Contribution from biomass CHP and hydrogen fuel cells[37] are seen in the green gas heating scenario.

Grid electricity from the transmission system remains vital in all scenarios in 2050 by performing a prominent role in balancing electricity supply and demand within the Arc region. This grid electricity supply varies in accordance to the availability of local generation. As the national electricity system decarbonises (nuclear, offshore wind and PV and gas fired generation with CCS), the use of local non-renewable generation is not economically viable due to high carbon costs (99 £/tCO_2) in 2050,[38] unless used for flexibility purposes. However, in 2050 the delivery of low carbon electricity from the transmission network is limited due to grid congestion and capacity limitations with grid supply points.

37 Fuel cells are used in the green gas strategy as a heating technology (heat driven). Fuel cells are preferred for their co-generation of electricity and heat which makes it cost effective compared to a dedicated hydrogen fuelled power generation.

38 BEIS (2018). Short-Term traded carbon values.

7.2.2.3 Emissions

The emission calculations presented below only include emissions that can be attributed locally such as heat supply, electricity generation, hydrogen production, and local non-heating uses of fuels (gas, biomass, solid waste, oil and solid fuel). The emission values therefore do not include transmission related emissions. Within the Arc region, across all Arc scenarios, the annual emissions decline from 10.96 $MtCO_2$ (Million tonnes of CO_2 equivalent) in 2015 to under 2 $MtCO_2$ for electric heating dominated heating strategies by 2050. In contrast, the heat network strategy accounts for the highest emissions with an average of 6$MtCO_2$ and green gas averaging 3.5$MtCO_2$ across Arc scenarios as shown in Figure 35(a).

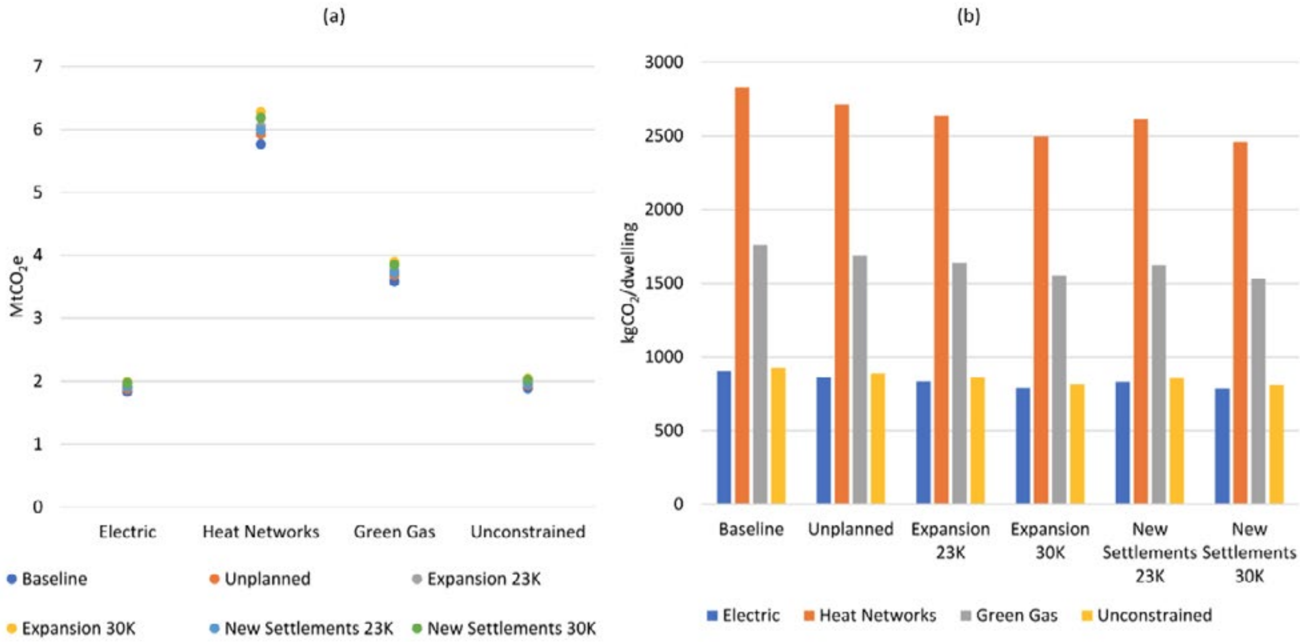


Figure 35: Emissions calculated for year 2050 across scenarios and heating strategies (a) Annual Emissions – $MtCO_2$ and (b) emissions produced as $kgCO_2$/dwelling.

In proportion to the energy produced, the Expansion 30k scenario shows the highest annual emissions in 2050 particularly for the green-gas and heat-network strategies. The Baseline scenario annual emissions are the lowest, where, the difference between it and Expansion 30k scenario in the heat network strategy is ~540$ktCO_2$ and in green gas is 420$ktCO_2$. The emissions produced per household shows far more variations than the annual emissions between the Arc scenarios, this is shown in Figure 35(b). The Expansion scenarios (both 23k and 30k variants) in 2050 on average produce ~2500$kgCO_2$/year/household for the heat network strategy, almost 15% lower compared with the Baseline scenario.

By 2050, across all Arc scenarios, the 'electric' heat strategy emissions in the residential and commercial sectors decrease to nearly zero as electricity replaces 100% of overall fuel demand for heating and electricity is mainly supplied by the transmission network (almost carbon free), V2G and renewables. The extra emissions accounted for in the 'electric' strategy are from the non-heating use of fuels mainly from the industrial sector.

Further replacement of these non-renewable fuels with biogas, hydrogen or decarbonised electricity would most likely result in the achievement of 'net-zero' emissions locally. In comparison, even though it's almost wholly electricity driven, in the unconstrained heat supply strategy, an additional ~50ktCO_2 of emissions are accounted for the energy produced from biomass and waste in 2050.

The heating strategies with high natural gas, biomass and solid waste use account for ~3.5–6.5 MtCO_2 of emissions in 2050. Replacement of natural gas with green gases such as biomethane and hydrogen, has the potential to achieve emission levels less than half of that in 2015. Consequently, green gas strategy has 2MtCO_2 lower annual emission in 2050 compared to the district heating strategy. Large scale hydrogen production by steam methane reforming (SMR) is equipped with CCS to capture ~95% of emissions.[39] The rollout of national CCs infrastructure is assumed alongside the deployment of large scale SMR facilities. However, hydrogen transportation flows are facilitated by existing natural gas transmission pipelines into the Arc region. Emissions from hydrogen production are allocated as a proportion of consumption from within the Arc. Anaerobic Digestion (AD) or gasification of organic material have similar carbon footprint as SMR with CCS and are used to produce biogas.

In the district heating strategy 30% of heat is produced by natural gas – CHP units and boilers. This adds a substantial amount of emissions (0.184 kgCO_2/kWh) on top of the emissions from non-heating fuel uses within the region. Further emissions are also included from the use of biomass (0.0127 kgCO_2/kWh) and solid waste (0.008 kgCO_2/kWh) together they account for 50% of the total heat supply.

7.2.2.4 Operational costs

The annual operational costs focus on the operation of electricity, gas, heating and hydrogen supply systems within each Arc scenario and heat supply strategy. The operational cost calculations include: (i) distribution system operating costs comprising of fixed and variable costs of operating different technologies, and fuel costs for biomass and solid waste; and (ii) costs for transmission gas and electricity supply which includes total electricity and gas flows from transmission supply points into the Arc region. Within both distribution and transmission system calculations, carbon costs are applied as appropriate. A breakdown of operational costs for the Baseline scenario in 2050 is shown in Figure 36 (bar chart). Additionally, annual operational costs in 2050 for the Arc-region across the scenarios and strategies are shown as dots.

The operational costs of energy supply within the Arc region are highest in the Expansion 30k scenario and lowest in the Baseline scenario in line with final energy demand and supply variations across the Arc scenarios. District heating and green gas strategies stand out with the highest distribution system operational costs by 2050 mainly due to high carbon costs (use of natural gas) and additional operating costs associated with the operation of heat networks and hydrogen supply systems. Given the technological maturity of large-scale hydrogen production at present, it is assumed that these remain operationally expensive in relative terms even by the 2040s.

39 CCC (2019). Net Zero The UK' s contribution to stopping global warming.

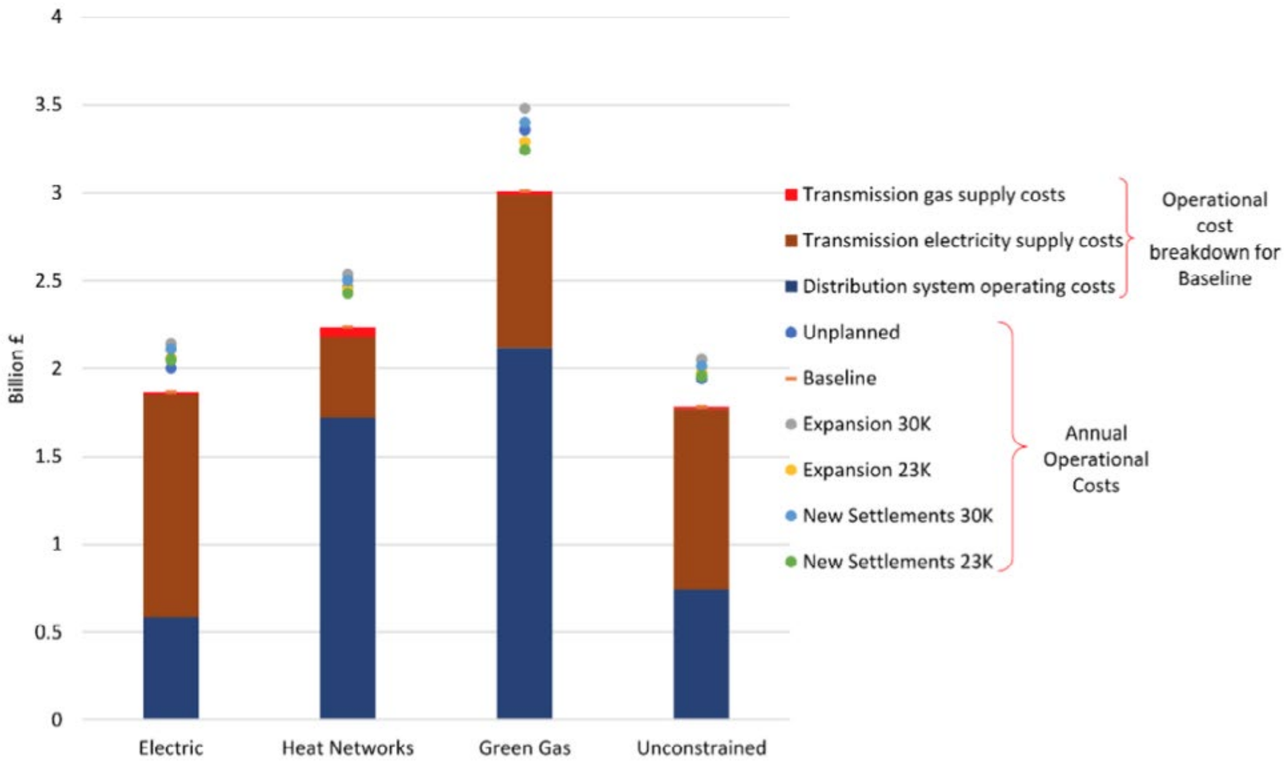


Figure 36: Annual operational costs for 2050 across Arc scenarios and heat supply strategies.

Consequently, green gas strategy has the highest distribution system operating costs across all scenarios in 2050. In contrast, transmission electricity supply costs are highest in electricity driven heating strategies (electric and unconstrained). Unconstrained has lower transmission electricity supply costs compared to the electric strategy, as some of this is substituted by waste-to-energy plants due to a combination of transmission to distribution capacity limits and competitive marginal unit costs.

7.2.3 Strategy and scenario resiliency

A limited set of sensitivity studies is performed for the Expansion 30k scenario in year 2050 across all heating strategies. The impact on key metrics such as energy demand, electricity and heat supply, emissions and costs are analysed. Sensitivity analysis is performed on the following independent variables:

Impact of peak demand: 10 % increase in the demand is assumed during the peak period (5pm, 6pm, 7pm) for electricity and gas non heating, and overall heating demand.

Impact of more/less wind: A 10% increase and decrease of wind speeds from the base[40] level is assumed.

40 The sensitivity studies base refers to the data/inputs used in the main scenario studies.

Impact of DSM: DSM schemes are made available to the system operator to switch non-heating electricity demand (including EV charging demand) from peak to specified off-peak hours. 10 % is assigned as the maximum demand potential that can be shifted from a peak hour. Here peak hours are extended (5pm to 8pm) to cover the EV charging peak (7 to 8pm). The off-peak hours are (9am to 2pm) and (9pm to 12 midnight).

Efficiency improvements in dwellings: it is assumed that there will be additional ambitious efficiency improvements in homes and appliances, which further reduces all electricity and gas non heating demands, and overall heating demands by 10%.

7.2.3.1 Impact of peak demand

A 10% increase in electricity and gas-non heating and overall heating demand during peak periods is applied to the Expansion 30k scenario in 2050.The impact this change has on overall electricity demand during the peak hour (7pm) during a typical winter's day in 2050 across heating strategies is shown in Figure 37.

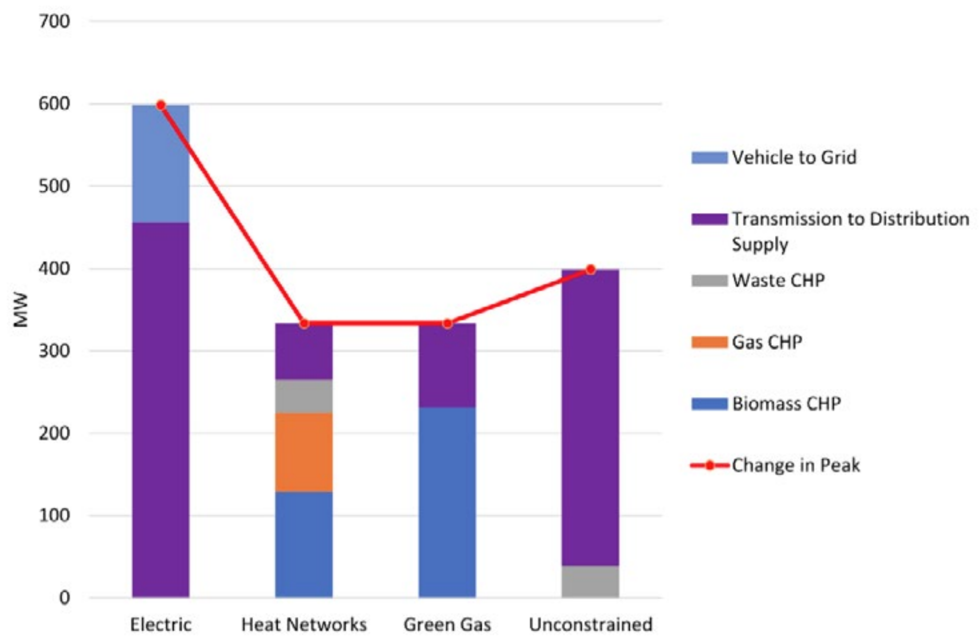


Figure 37: Change in electricity demand and electricity supply at peak hour (7pm) across heating strategies in 2050.

The biggest change in peak electricity demand (~0.6GW) has occurred in the electric heating strategy. This additional electricity demand is met by transmission electricity supply and vehicle to grid services. In the case of V2G, uncertainties persist regarding consumer behaviour; therefore the transmission to distribution electricity supply needs to be sufficient to cover the potential shortage in V2G supplies. Otherwise, ancillary services from non-renewable distributed generators should be procured, this however will add additional operational costs (fuel and carbon).

The use of co-generation units has the advantage of supporting the increase in both heat and non-heat electricity peak demand. This is shown in the heat-network and green-gas strategies where additional electricity supply is provided by CHP units. The reminder of the electricity demand is met by transmission grid electricity and/or V2G services.

As the peak heating demand increases (increase of 0.5GW at the peak hour), additional heat supplies are used as shown in Figure 38 across the heating strategies. This reflects the value offered by additional or backup heat supply capacity to support sudden increases in peak heating demand.

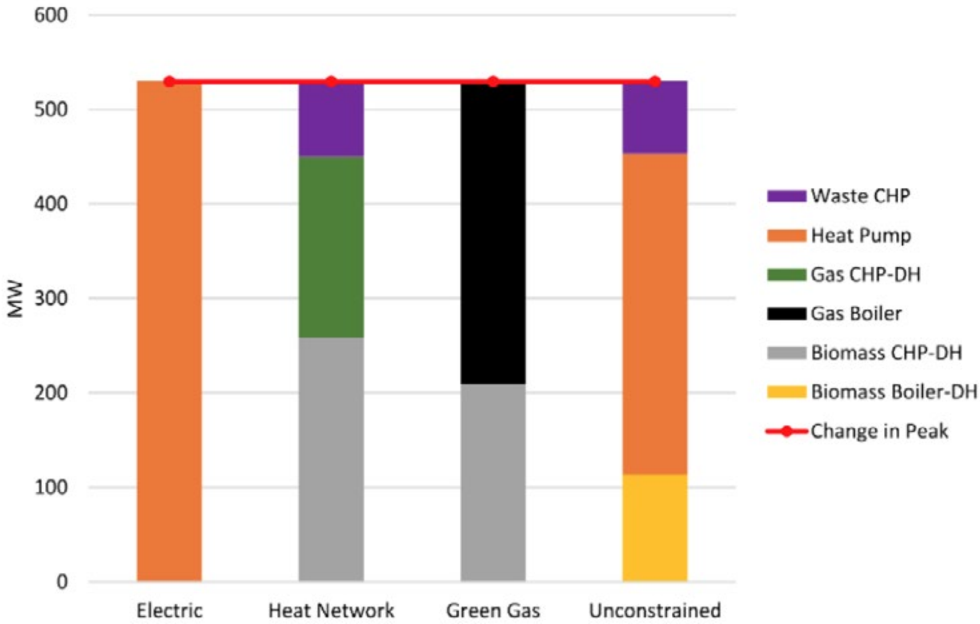


Figure 38: Change in heat demand and heat supply at peak hour (7pm) across heating strategies in 2050.

7.2.3.2 Impact of wind variations

A 10% increase and decrease in Arc region wind speeds was considered. For a particular day in winter (2050), variation in wind speeds results in a wind power generation profile as shown in Figure 39.

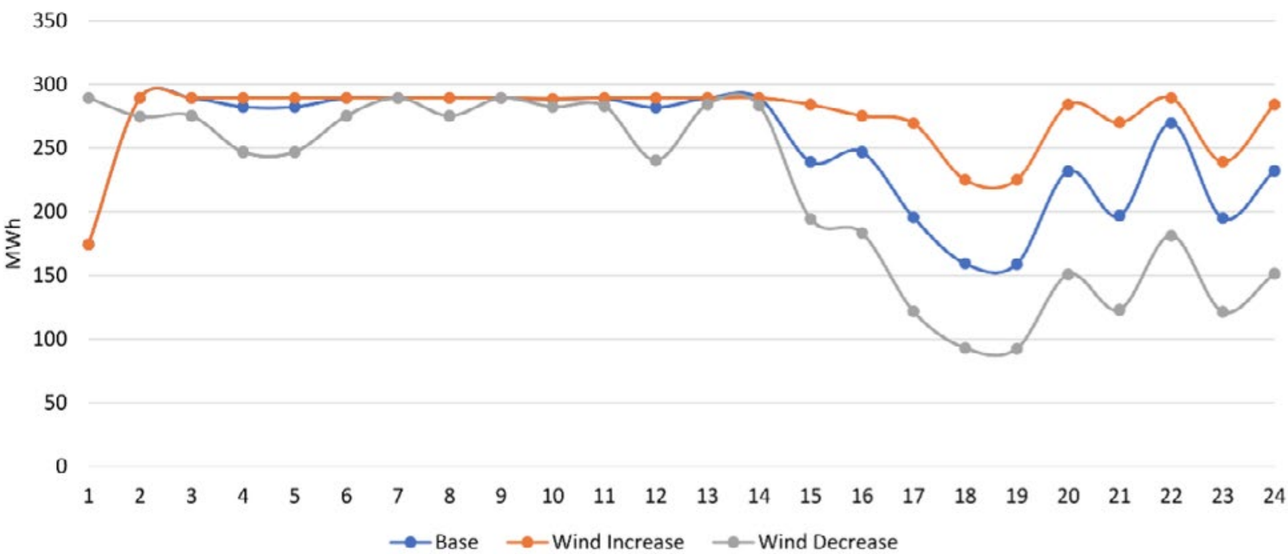


Figure 39: Change in wind power output subjected to 10% increase and decrease in wind speed within the Arc region in 2050.

The maximum power output from wind generators within the Arc region is limited to ~300MW in 2050. Considering the electricity peak demand of 11GW in the 'electric' heating strategy, full wind power output contributes to only 2.5% of the peak demand with base wind speeds. Therefore, with respect to the base wind power output, more/less wind speed would only result in a maximum change in wind power output power of +/- 66MW.

The impact of change in local wind speed therefore does not hugely influence the electricity supply mix in any heating strategy for the Arc region, unless there is a considerable increase in the installed wind power capacity within the Arc and consequently contribution of wind power output to the overall electricity supply mix.

7.2.3.3 Impact of Demand Side Management (DSM)

Demand Side Management (DSM) schemes are available for the system operator to switch pre-agreed electricity demand; non-heating including demand for EV charging, from peak hours to off peak hours, such that the total operating costs are minimised. The DSM scheme implemented allows a maximum shifting capability of 10% demand at peak hours. Figure 40 shows the DSM scheme in effect for a day in winter, across different heating strategies in 2050. The figure shows the additional demand assigned (positive) and demand shifted (negative) with respect to the base electricity demand.

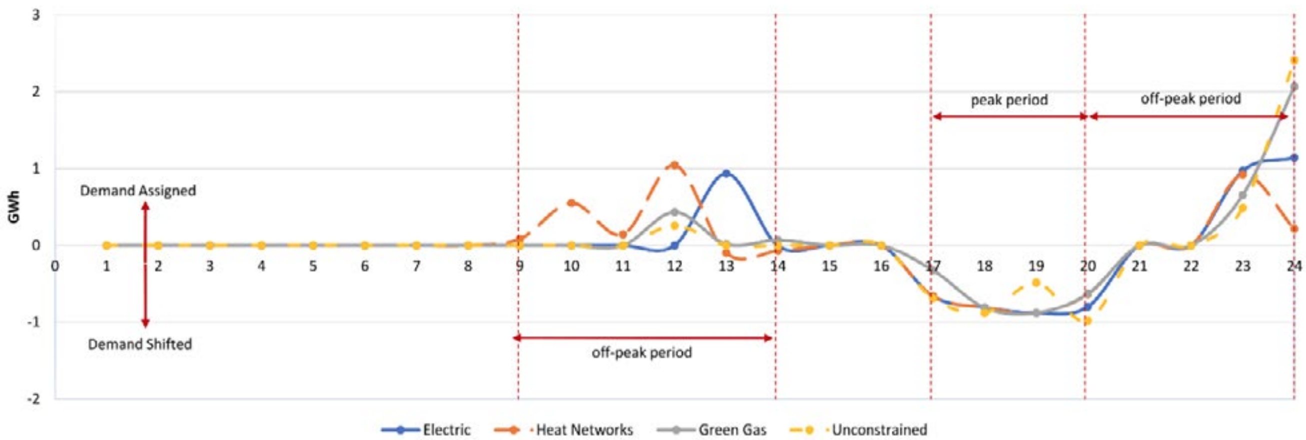


Figure 40: Change in electricity demand due to implementation of DSM scheme in 2050.

Across all strategies, on average around 3GWh of electricity demand is shifted from peak hours to off-peak hours. The demand assignment is performed incrementally between off-peak hours to ensure power system stability. Approximately ~70% of the shifted demand is assigned to the period between 10pm and 12am across electric, unconstrained and green gas heat strategies. In heat-networks strategy the electricity demand is assigned equally between 9am-2pm and 9pm-12am periods. This allows cost-effective combination of CHP units (already running for heat supply) and transmission grid electricity supply to meet the assigned demands.

Figure 41(a) shows the change in electricity imports from the transmission network and supply from distributed generators during the off-peak hours over a day in 2050. The reduction of demand during peak hours is mirrored by decreased operation of distributed generation plants, and transmission electricity imports as shown in Figure 41(b).

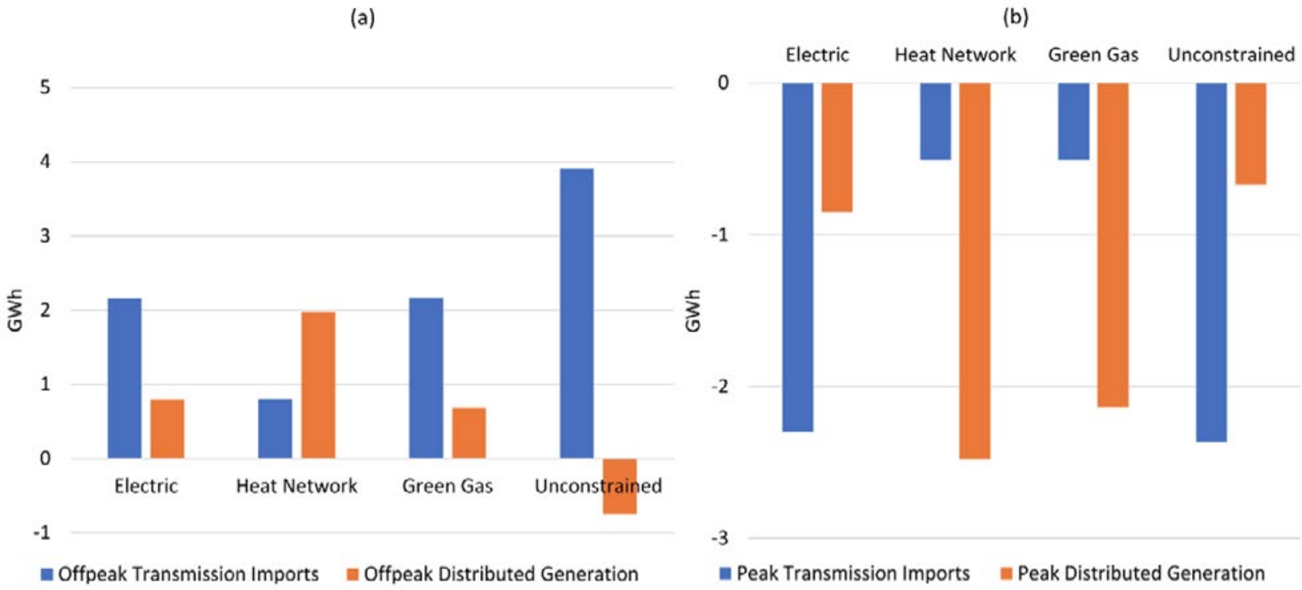


Figure 41: Change in electricity supply from the transmission network and distributed generators in 2050. (a) during off-peak hours and (b) during peak hours where (+) ve = increase in electricity supply and (-) ve = decrease in electricity supply.

The extra demand during off-peak hours is primarily met by transmission grid electricity. Transmission grid electricity is cheaper during these off-peak hours compared to operating non-renewable distributed generators mainly in the electric and unconstrained heating strategies. In contrast, in district heating strategy the available distributed generators (CHP units) are dispatched in combination with transmission grid electricity to meet the additional demand. Heat networks strategy makes the greatest use of distributed generators to supply the extra electricity demand during off-peak hours compared to other heat supply strategies.

Table 5 shows the annual cost savings that the system operator can accrue by utilising the DSM scheme.

Table 5: Annual operational cost savings using DSM scheme in 2050	
Strategy	Annual operational cost savings (£million)
Electric	7.18
Heat Networks	0.24
Green Gas	0.84
Unconstrained	3.39

In both electric and unconstrained modes, the cost savings are high due to the reduction of expensive transmission electricity supplies during peak hours. The use of V2G services are also reduced since the tariff system for V2G services (e.g. Fast Frequency Response and Short-Term Operating Reserve) during peak hours is unattractive for a unit of power exported to the grid.[41]

The heat networks strategy shows the lowest savings as the expensive distributed generators (CHP units) that are switched off during peak hours (~2GWh shifted), are then used to produce a similar amount of electricity during off-peak hours. Consequently, the net savings are smaller compared to green gas where off-peak cheap transmission electricity supplies are used to meet the electricity demand instead of distributed generators – CHP or V2G.

7.2.3.4 Impact of demand reduction due to dwelling efficiency improvements

Further efficiency improvements in dwellings and appliances are expected to reduce demands; a 10% reduction in heating, non-heat electricity and gas was assessed in 2050. Figure 42 shows the annual energy demand across heating strategies with and without demand reduction.

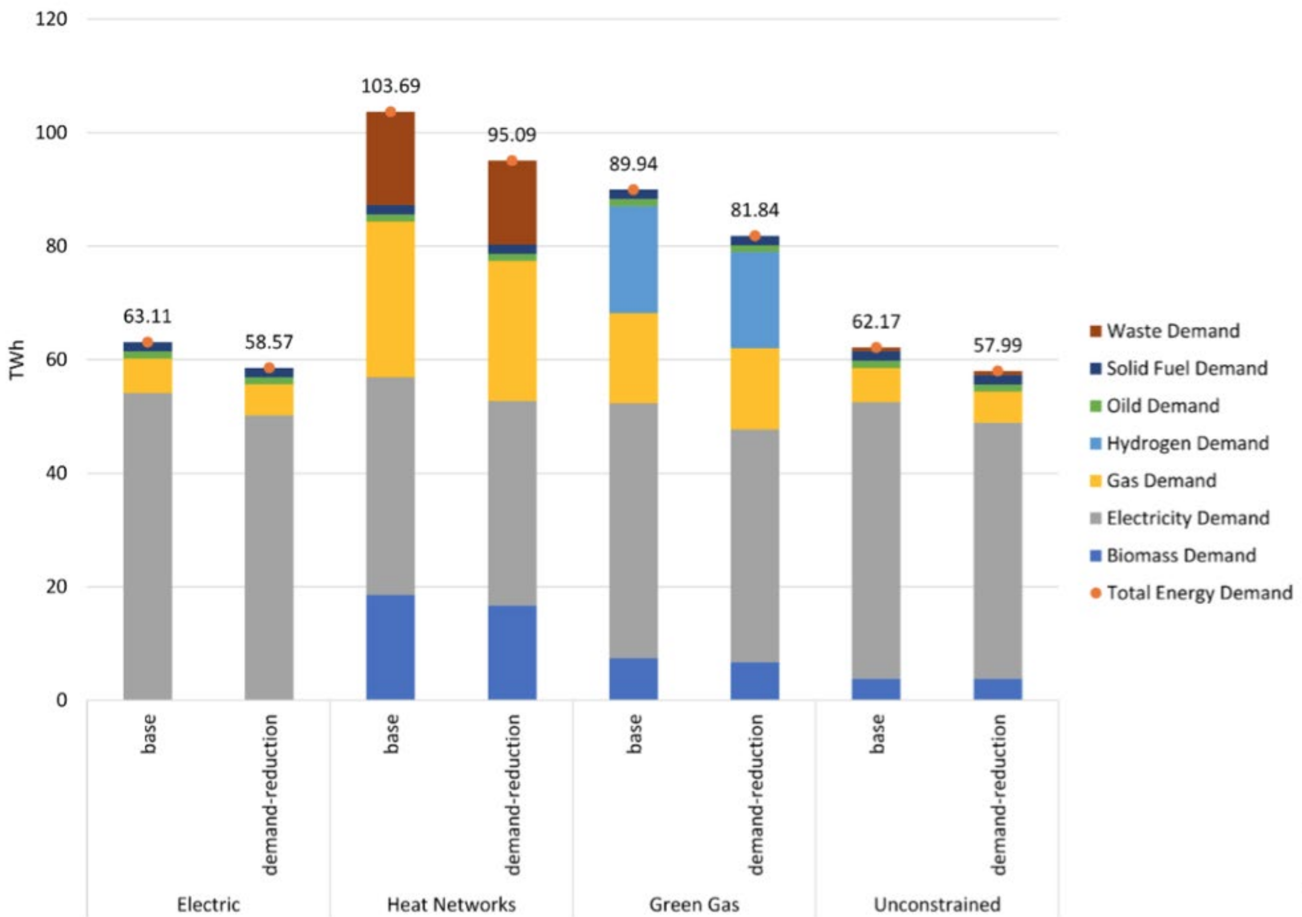


Figure 42: Impact of further efficiency improvements in dwellings on annual energy demand in 2050.

41 Payne, G. and Cox, C. (2019). Understanding the True Value of V2G.

The impact of efficiency improvements in dwellings on overall heating demand and non-heating electricity/gas demand is a reduction of annual heating demand by 8TWh in both green gas and heat network strategies. In electric dominant strategies the annual energy demand is reduced by 4.5TWh. There are no changes to solid fuel and oil demand as they mainly remain in use within the industrial sector. Table 6 shows the annual demand reduction across heating strategies in 2050. The values are derived from the share of heating demand by technology and its efficiency.

Table 6: Annual demand reduction (TWh) across heating strategies in 2050 due to efficiency improvements

Fuel	Electric	Heat Networks	Green Gas	Unconstrained
Biomass	0	1.85	0.74	0.03
Electricity	3.94	2.36	3.89	3.54
Natural gas	0.61	2.74	1.59	0.61
Hydrogen	0	0	1.88	0
Waste	0	1.64	0	0.002
Total demand reduction	~4.54	~8.60	~8.10	~4.17

In the 'electric' heating strategy, heat supply from heat pumps is reduced significantly. Similar behaviour is observed across other strategies and consequently considerable reductions are seen in annual electricity demand. Heat supply output by hydrogen boilers and gas boilers are significantly reduced in the green gas strategy, and therefore annual demand for natural gas and hydrogen. In district heating strategy a large decrease in the utilisation of almost all-natural gas fired heat technologies produces the largest fall (2.74TWh) in annual natural gas demand.

A decrease in the use of electric heating technologies greatly reduces the reliance on electricity supplied by the transmission grid. Across all strategies, the annual supply of transmission grid electricity decreases by 2.5-3.5TWh. There is no significant change among other distributed technologies including V2G.

Dwelling efficiency improvements and the use of efficient appliances result in overall reduction in demand and therefore changes in supply. This in turn influences overall operating costs and emissions across different heating strategies. Figure 43 shows the impact on annual operating costs and emissions in 2050.

The implementation of efficiency improvements in the electric dominant heating strategies – electric and unconstrained show cost savings of ~£150M, in contrast three times higher savings are possible in the heat networks and green gas strategies. This is due to operational cost savings from non-renewable electricity generation (CHP units) and their associated fuel costs (gas, biomass and solid waste). The savings in non-renewable fuels are reflected by reductions in overall emissions of 550ktCO_2 in heat networks and ~300ktCO_2 in green gas heat strategies.

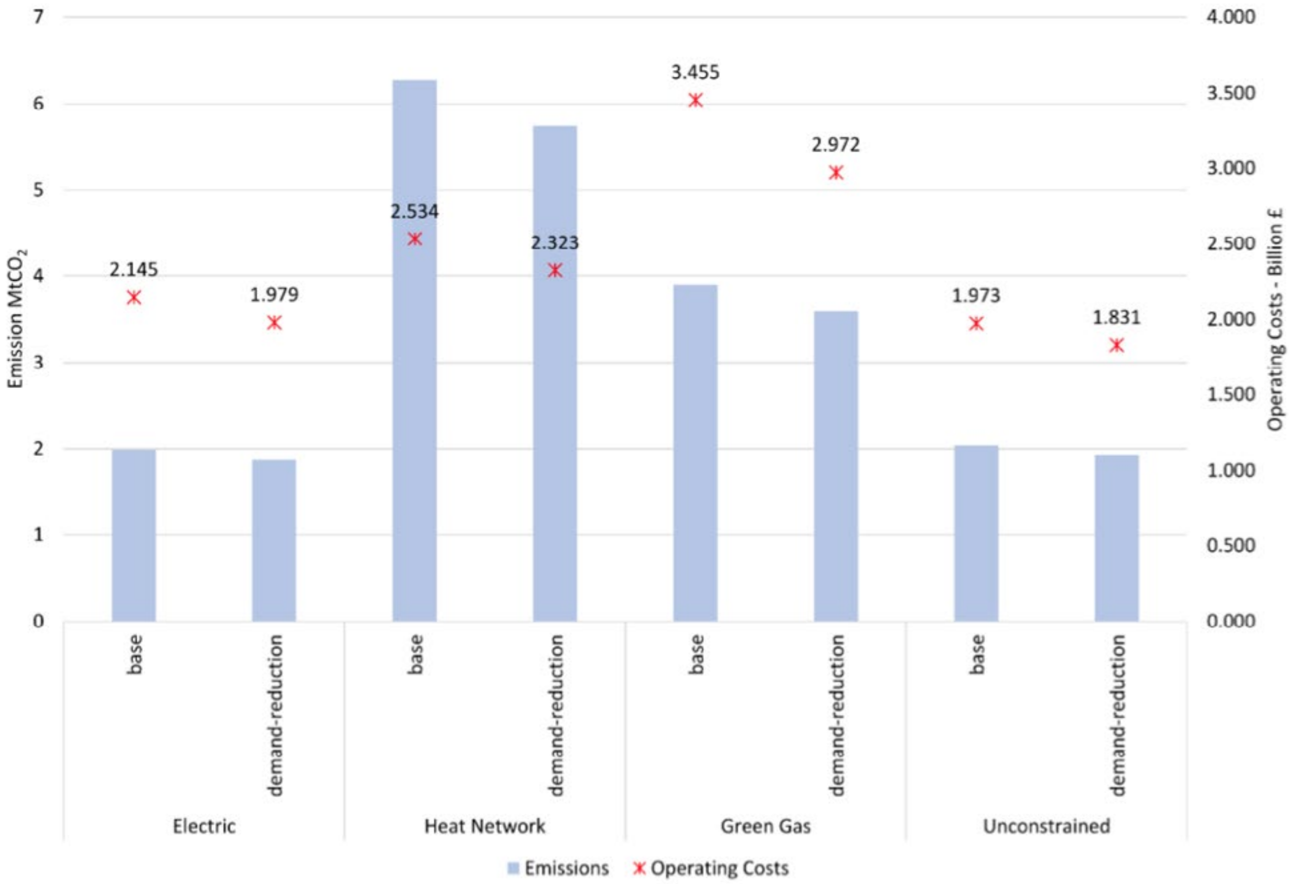


Figure 43: Impact on annual operating costs and emissions due to reduction in demand (2050).

7.2.4 Scenario and heat strategy costs

The annualised cumulative total costs (2015-2050) of implementing energy supply solutions across heat supply strategies and selected Arc scenarios per household (dwelling) are shown in Figure 44. Operational costs were determined by the model (objective function). These costs include primary and secondary energy resources supplies such as natural gas and electricity, and power generation variable costs and carbon costs. Network costs such as for new power lines, pipes and investment costs in new power and heat generation capacities within the Arc are included in the calculation of overall costs. Network and generation capacity reinforcements outside the Arc region (transmission and other energy hubs) are not considered.

In 2015, given a central gas price outlook, household costs were ~£820 per annum. In the Baseline scenario, implementation of the 'heat network' strategy has the largest annualised household costs (2015-2050), approximately £1,180 more than the Baseline (2015) and at least £640 per annum greater than the next costliest strategy 'unconstrained'.

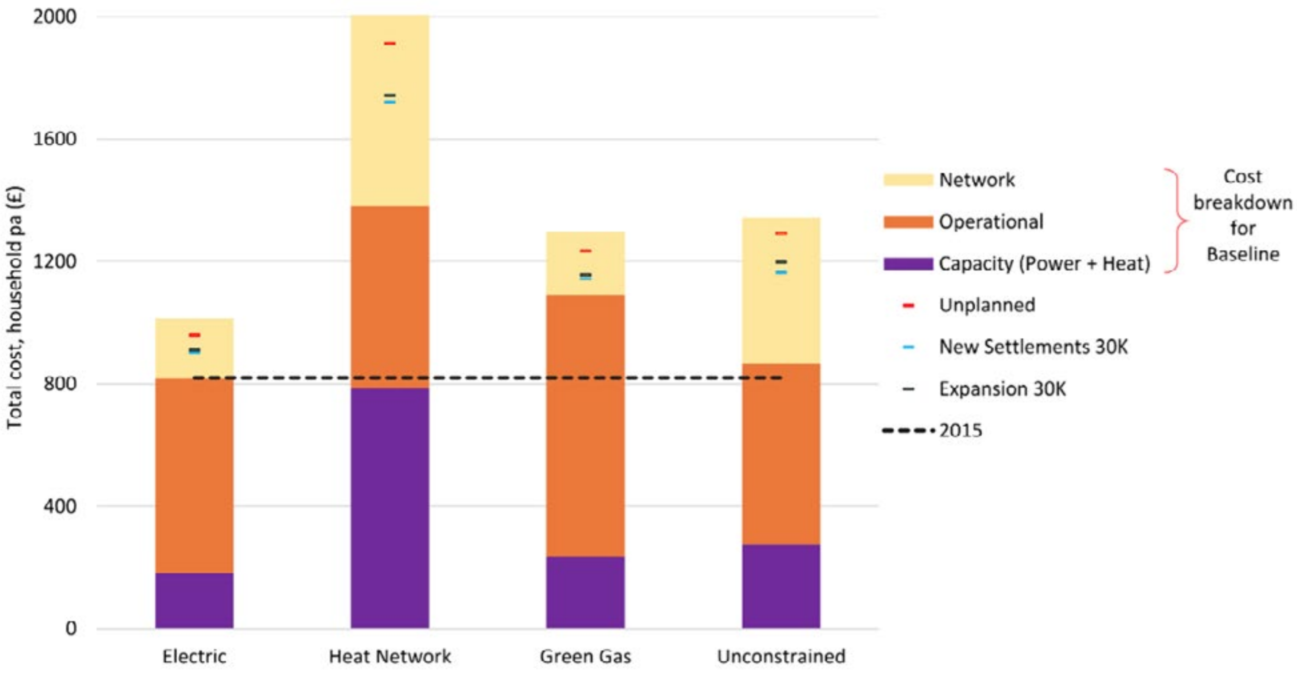


Figure 44: Annualised cumulative (2015-2050) costs per household.

Costs associated with 'power and heat' generation capacity are largest in the 'heat network' strategy irrespective of scenario, this is mainly due to the use of expensive CHP (gas, biomass, waste) systems. These costs are lower in the other strategies. The 'electric' strategy shows the lowest power and heat capacity costs, mainly due to continual reductions in heat pump capital costs from 2030s onwards. This is followed by 'green gas' where cost effective gas boilers (with mixture of gas, hydrogen and biogas) and hydrogen boilers (via dedicated hydrogen pipes) are deployed. The unconstrained strategy across all scenarios primarily consists of the deployment of heat pumps and to a lesser degree on more expensive CHP systems.

In the green gas strategy, more than 70% of hydrogen production within the Arc region is from SMR with CCS. Additionally, there are small scale electrolysers deployed alongside renewable generators (wind and PV) or to produce hydrogen if electricity prices are cheaper than natural gas. Biogas can be injected up to a maximum of 20% by volume into existing gas pipelines. In 2050, the Expansion 30k scenario has 5TWh of biogas injected into the gas network. The production of biogas in the green gas strategy is through Anaerobic Digestion (AD) of organic matter. With the availability of feedstock, biogas becomes a competitive alternative for natural gas. The capital costs of SMR, electrolysers and AD plants are included in the cost calculations.

Network related costs are almost three times larger in the heat network strategy when compared with the other strategies across the scenario space. This is mainly due to high costs related to civils (digging trenches of approximately three times deeper than electricity/gas lines and pipes), pipes and connections (hydraulic interface units and connections within buildings).

In contrast, with decarbonisation of the gas system (green gas strategy) it was assumed that given the ongoing IMRP (Iron mains replacement programme – replacement of iron pipes with polyethylene ones), sections of the gas distribution system would be repurposed for the use of hydrogen alongside up to 20% (by volume) of hydrogen injection into the remaining gas distribution system. In the Expansion 30k scenario, annual hydrogen injected into the gas network was ~1.5TWh. The repurposing of the gas distribution system had the impact of reducing excavation/civil work and therefore overall network costs. For the New Settlements and Expansion scenarios a multiplier was added to the cost of laying new hydrogen pipes as no existing gas pipes would be available for repurposing. The cost associated with household appliances was not modelled.

Investment in the electrical distribution grid is highest in the 'electric' strategy. Despite heavy investment due to the high costs of underground power lines (for densely populated areas) as opposed to over-ground power distribution and transmission lines, overall network costs remain lower than the strategies for gas/hydrogen distribution and heat network systems.

The second largest investment in the electrical grid across all scenarios occurs in the unconstrained strategy. This investment is supplemented by heat networks to take advantage of large waste/biomass CHP-boiler systems to provide heat and power.

Operational costs are determined by the energy supply model and take account of all aspects of energy flows from transmission systems, through a multitude of interconnected distribution systems (multi-vector approach) to meet demand. Operationally, the green gas strategy shows the highest costs. This is mainly due to higher fuel resource costs associated with gas, biomass and production of hydrogen. The outputs show that more than 70% of hydrogen is produced by using SMR. All renewables are fully utilised to support the electricity system and there is no 'free' electricity available, hence limited production from electrolysis systems. The continued use of gas weighs heavily on overall costs (fuel and carbon) in the 2030s but less so by 2050.

The heat network strategy operational costs across scenarios are competitive with electric and unconstrained strategies. This is mainly due to the use of highly efficient co-generation units where local electricity generation replaces more expensive transmission grid electricity especially during peak hours when only higher marginal cost plants are available to balance the system. The capacity of co-generation units under high overall efficiencies allows it to meet both heat and electricity demand within the region without heavy reliance on the electricity transmission network.

Operational costs are lowest in the 'unconstrained' strategy across all scenarios. This is to be expected as the model can choose among several technologies to achieve low overall operational costs for power and heating. But since the optimisation process only considers operational costs, when capital costs for network and capacity additions are included, the total annualised costs to implement the unconstrained strategy rises to second largest on a per household annualised basis.

The electric strategy across all scenarios has the second lowest operational costs, as the system decarbonises mainly through the use of nuclear and near zero marginal cost plants for the production of electricity and the use of high efficiency electrical heating systems by 2050.

Across scenarios and strategies, the annualised household costs are reduced from Baseline values. This is in part due to improved insulation and efficiencies reducing the demand for energy services per dwelling despite an increase in overall population and homes. Additionally, there are benefits to denser heat demand locations, these can accrue economies of scale especially with regards to heat network infrastructure. The impact of this is illustrated with the '30k' scenarios where reductions in dwelling costs of up to £300 per annum can be observed.

7.2.5 Energy summary

The modelling process for the Arc analysis has generated a diverse range of options and pathways from production and generation of energy through to the choice of supply networks and end use technologies.

Key modelling matrices in 2050 such as emissions, energy consumption and costs in comparison with the Baseline business-as-usual (BaU) 2015 case are shown in Figure 45. The outputs of 2050 are shown under each strategy investigated – Electric, Heat Networks, Green Gas and Unconstrained (4 columns). The figure follows the order to first describe the heat strategy chosen in 2050 (first row of each column). The descriptions to the metrics shown in the summary figure are described in Table 7.

Table 7: Parameter descriptions for the summary diagram

Metric	Description
1. Heat supply & demand	**The annual heating demand (varies across Arc-scenarios).** **Share of heat supply by different technologies.**
2. Energy demand	**Annual energy demand for the Baseline scenario.** **Change (+ve) in annual energy demand in other Arc scenarios with respect to the Baseline scenario.**
3. Electricity supply & demand	**Share of electricity supply by technology.** **The largest electricity peak demand (in this case Expansion 30k scenario)** **Comparison of annual electricity demand between the Baseline and Expansion scenarios.**
4. Natural gas supply	**Annual natural gas supply.** **The lowest and the highest annual gas supply among Arc scenarios.**
5. Emissions	**Annual emissions (ktCO_2).** **Change in emissions across Arc scenarios with respect to Baseline (+ve).** **Annual emissions per dwelling (kgCO_2/dwelling).** **Change in annual emissions per dwelling across Arc scenarios with respect to Baseline (-ve).**
6. Costs	**Cumulative annual costs to implement a strategy up to 2050 described per household.** **Comparison of costs between the Baseline and the lowest Arc scenario.** **Breakdown of costs as a percentage.**

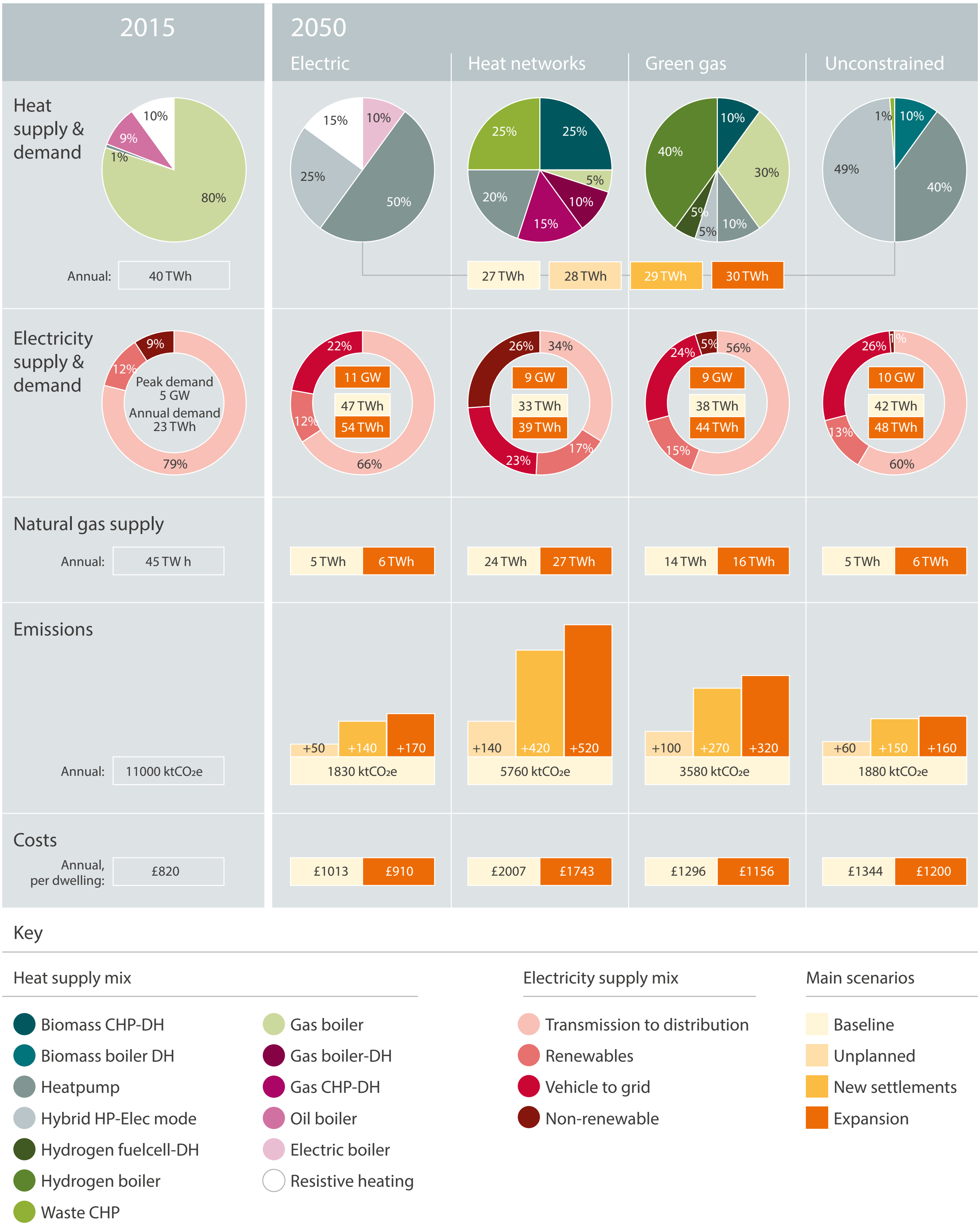


Figure 45: Summary of key output metrics across heating strategies and scenarios in 2050.

7.2.5.1 Energy demand

The scenarios with the highest population growth rates (30k variants) have the highest annual demand 70TWh (average across strategies) in 2050. This is an additional 10TWh demand compared to the Baseline scenario.

The 'electric' heating strategies have an overall demand for energy in 2050 which is lower than BaU (2015). This is mainly due to the utilisation of highly efficient heat pumps. In contrast with the heat network (and to a lesser degree green gas) strategy which predominantly use CHP units, whilst being efficient do not provide the performance offered by heat pumps. This results in final energy demand in 2050 that is nearly doubled compared with the electric strategy.

7.2.5.2 Electricity supply and demand

In 'electric' strategies across the 30k scenario variants, the combination of EV charging and electrification of heat more than doubles both electricity peak (~11GW) and annual demand (~54TWh) in 2050 compared with 2015. Of this, EV charging accounts for approximately 4GW of peak electricity and 15TWh of annual demand.

Electricity demand met by supplies from within the Arc region in 2050 varies from 34% in an electric strategy to 66% in strategies where co-generation units are employed (heat networks and less so in green gas). Electricity supplies from EV utilisation of vehicle to grid services provides approximately 20% of the electrical demand alongside renewables accounting for 15%. In heat networks and green gas strategies additional generation is from gas, biomass or waste CHP units.

The national electricity transmission system maintains a prominent role in balancing electricity supply and demand within the Arc region. Excluding the heat networks strategy, other strategies across all scenarios require more than 50% of electricity demand to be met by supplies from the electricity transmission system.

7.2.5.3 Gas demand

Annual demand for natural gas drops significantly across the Arc scenario space by 2050, to less than half of that in 2015 (~45TWh). In almost all electricity-based heating strategies in 2050 (electric and unconstrained) the gas demand declines even further to 5TWh/year (90% lower). As natural gas has no significant role in these electric heating strategies, the variation in population and dwellings across the Arc scenarios has little or no impact on the gas demand. The use of natural gas is highest (~12TWh) in the district heating strategy in 2050 as it is mainly used to produce heat via district heating CHP units and boilers. In the green gas heating strategy natural gas demand declines to 8TWh as biomethane and hydrogen are blended into the gas network.

7.2.5.4 Options for decarbonising heat

The overall demand for heating declines by 2050 across all scenarios due to ambitious 25% savings from improved insulation, thermal comfort in the building stock and a 100% smart meter rollout across the region.

In line with the population and dwelling variations, the Expansion 30k scenario has the highest heating demand ~30TWh which is an additional 4TWh of demand compared to the Baseline scenario.

The heat supply strategy options illustrate ways of meeting the demand for heating up to 2050 across Arc scenarios. The heat supply options and emissions in the Arc region are described as follows:

Electrification of heat

Decarbonisation of heat could be achieved by switching from a system with predominately gas boilers to a system built to accommodate heat pumps (dwelling level and larger scale units connected to a heat network), resistive heating and storage, and running these on decarbonised electricity. The model outputs across all scenarios showed that this would require significant additional electrical generating and network capacity. Given the overall costs alongside near zero emissions in the residential and commercial sectors, the electric strategy performs strongest across all key metrics compared with other strategies.

The implementation of an 'electric' strategy would experience many practical challenges. In scenarios where retrofitting of existing buildings is required the implementation of an 'electric' strategy would entail the requirement of radical change in infrastructure at the end user level, such as each household either acquiring a heat pump, resistive heating system or electric boiler. It becomes a great deal easier to incorporate this change on new dwellings proposed in the scenarios (especially in 'New Settlements' and 'Expansion').

The public's knowledge of technologies such as heat pumps is still limited, where awareness could be increased by government and industry via promotional exemplars. Confidence could be further enhanced by ensuring that installers abide by high standards during the design and installation process.

Decarbonisation of the gas distribution system

The UK is fortunate to a have an extensive gas transmission and distribution system. Locally the gas system is made up of 250,000km of underground pipes. Much of these assets are approximately 100 years old. Partial decarbonisation of the gas network can occur by mixing natural gas with hydrogen (20% by volume) and biomethane. This has the advantage that the changes for the end use appliances such as gas cookers and boilers can be kept to minimum.

The Iron Main Replacement Programme (IMRP) which started in 2002 has now reached the mid-point with the aim of completion by 2030. Although safety is the primary concern of the IMRP, a side benefit is that the new polyethylene pipes are suitable for full hydrogen flows and implies the possibility of near zero carbon emissions alongside relatively low network conversion costs. The challenge of producing hydrogen at such scale and to do so commercially and carbon free is one that is modelled within the 'green gas' strategy for the Arc scenarios. The 'green gas' simulation results show hydrogen production using SMR with CCS, which is expected to be technically and commercially viable in the 2030s to sustain the required flows and demands.

Hydrogen production using SMR is currently commercially competitive with electrolysis (powered by mainly renewables and other low carbon sources).[42] The overall annualised costs per household are at moderate levels when compared with the other strategies with emissions in 2050 that are over 70% lower than in 2015 across all scenarios.

Heat networks

The heat networks strategy for the scenarios focussed primarily on CHP based heating technologies but a heat network by definition is technology and fuel source neutral. Within the Arc scenarios and especially with 'New Settlements' and 'Expansion', given higher demand (for heat) densities and the possibility of synergies during the construction of heat networks and new dwellings, potential reductions in annual costs per dwelling are feasible. Overall costs are the highest across all strategies and scenarios whilst emission reductions are not as large as other strategies (~50% reduction from 2015 levels). Alternatively, if heat networks were attached to an equal capacity split between large heat pumps and CHPs, this would reduce heat capacity costs by over 25% but at the same time require strengthening of the electricity system which will undo some of the costs savings.

The implementation of a heat network strategy over all scenarios are shown to be feasible but several areas where progress needs to be made to fully realise the advantages offered by a heat source agnostic energy vector are identified, these include:

Economics

Across the scenario space heat networks strategies were shown to have the highest overall total costs including on a per household basis. This is mainly centred around the high capital costs for CHP plants, digging and laying of hot water pipes and connections to dwellings. Cost reductions will have to take place across all these areas for a 'heat network' based solution to succeed.

Lack of standardisation

There is no national organisation (such as national grid) to drive standardisation across the industry. There are several companies (which can be good for innovation) driving distinct operations regionally. But currently there is no universal approach to design layout or treatment of risks. This can lead to poor quality installations.

Perceived technological shortcoming

Whilst well established abroad (especially within EU), heat networks are still relatively new to the average UK consumer. Reports of poor service by energy services companies or others results in disproportional bad press like the one published by the CMA in 2018, "there were instances of poor service quality and cases where customers were paying 'considerably more' than for non-network heat".[43] Furthermore, there is a distinct lack of knowledge about heat networks (heating capabilities) including the charging methodology and awareness of the services offered.

42 CCC (2018). 'Hydrogen in a low-carbon economy.'

43 CMA (2018). Heat network market study.

Complexity

This can range from ownership issues such as who owns the network, who operates it, to what the grievance procedures are. With gas networks, as it is regulated, and though most people do not understand how the system operates they are comfortable in the knowledge that they are protected by a regulator. Additionally, to some degree people also like the fact that they own their boiler system.

7.2.5.5 Additional measures

A Demand Side Management (DSM) scheme across all strategies was evaluated in 2050. It assumed a maximum shifting capability of 10% electricity demand at peak to off peak periods. The DSM scheme, either via EVs or appliances and smart meters within dwellings reduced peak electricity demand by an average of 1GW across all strategies. This was translated into cost savings with minimal negative impact on emissions (despite the use of non-renewable based generation technologies).

DSM may seem like a panacea, as benefits include the possibility of reduced operational costs, relieving strain on the electricity network at times of stress and the potential of delaying or circumventing upgrades to the network. However, there are several areas that need to be addressed, including issues around increases in control complexity which could lead to an overly complicated management system and uncertainties regarding consumer behaviour and their interactions with DSM appliances.

The impact of a further 10% reduction in overall heating and non-heating demand in 2050 due to better insulation and efficiency improvements in dwellings was assessed across all strategies. This showed a reduction of annual heating demand of ~8TWh in both green gas and heat network strategies. In electric-dominant strategies the annual energy demand was reduced by 4.5TWh. The simulation outputs clearly show that before considering sophisticated and often expensive energy infrastructure solutions, the low hanging fruit of energy efficiency and insulation should be a pre-requisite for any local energy system developer.

7.2.5.6 Final thoughts

Electrification of heating in the Arc region was shown to be the most cost-effective way to meet emission targets across all Arc scenarios despite requiring significant additional generating and electrical network capacity. For existing dwellings this will entail radical change in infrastructure at the end user level such as installation of heat pumps and will be disruptive to householders. Before contemplating expensive energy infrastructure, insulation and energy efficiency solutions should be considered. Most low-carbon heat technologies across the scenarios and strategies analysed have high upfront capital costs in comparison with incumbent technologies and networks, such as gas distribution networks and boilers. This is a barrier for early deployment, but the UK must make a stand on this and absorb these early costs so that technological learning (costs and efficiencies) can be made and the workforce can be sufficiently trained to allow a relatively smooth transition to one of these low-carbon pathways.

As shown by this work, a holistic modelling approach is needed to take account of all local vectors alongside the backbone national system to assess credible pathways to supply local energy systems whilst meeting economic, sustainability and resiliency objectives.

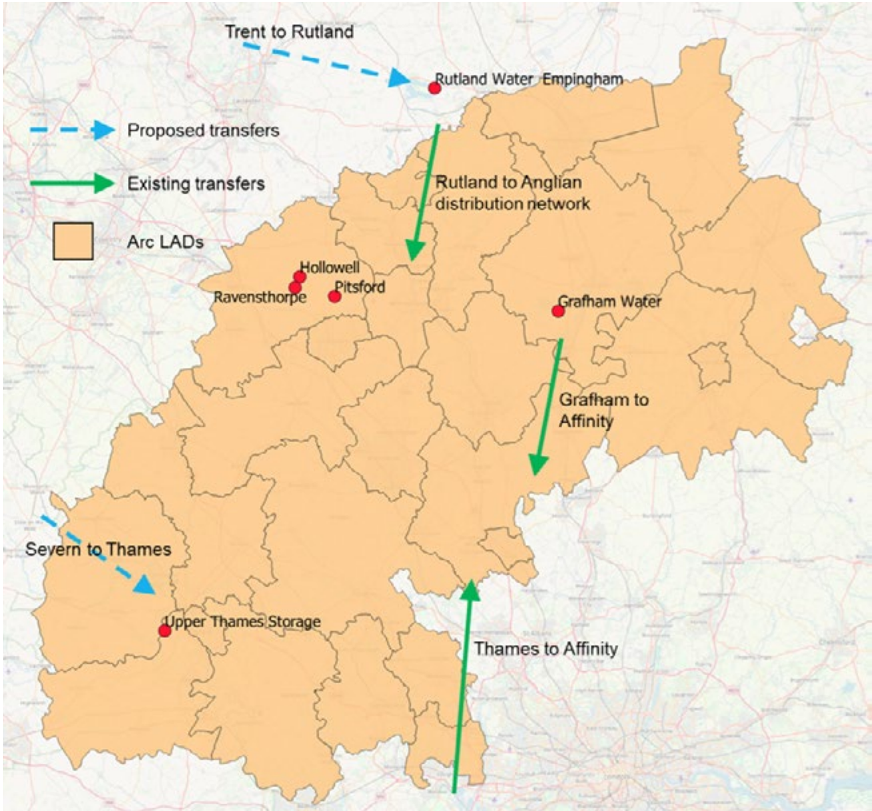
7.3 Water

The Arc is served by four water companies: Thames Water, Anglian Water, Cambridge Water and Affinity Water. For this assessment, we focus on the three key water resource zones (WRZ) in the Arc: SWOX (Oxford, Bicester, Banbury), Ruthamford North (Northampton, Peterborough, Wellingborough), and Ruthamford South (Bedford, Milton Keynes, Huntingdon). Cambridge is not explicitly included in these analyses because it is completely isolated in terms of water supply. The average per capita consumption of water in the Arc is 140l/d, which is higher than the national average of 124l/d.[44]

The surface water dominated regions are supplied by Farmoor reservoir in Oxford and the Ruthamford reservoirs (Rutland, Grafham and Pitsford) in Northamptonshire and Bedfordshire. The groundwater dominated regions are Luton/Hertfordshire and Cambridgeshire. All existing water sources in the region are already at capacity.

There are a range of large water infrastructure options that have been proposed in the region (see Figure 46) that may be able to accommodate the additional water demand that would result from population growth in the region. We describe these options and the regions they impact below:

Figure 46: Range of water infrastructure options.



44 WRMP Planning tables (2019). Environment Agency, dataset.

1. The proposed Severn to Thames transfer may provide up to 500Ml/d to Thames Water. This would directly increase the supply for Oxford, but could also increase the water supply for Luton (if an agreement is made with Affinity Water). Increased supply for Luton may also reduce the need for import of water from Anglian Water at Grafham (in Bedfordshire) and thus affect supply across the entire Western portion of the Arc. The Severn to Thames transfer would require re-direction of water from Lake Vyrnwy in Wales away from United Utilities when the transfer is in use, possibly reducing the resilience of water supply in Manchester and Liverpool.
2. The proposed South Lincolnshire reservoir near Spalding would be able to store 30,000Ml for use by Anglian Water and supply over 100Ml/d to Northamptonshire. This would increase supply for the region but would also enable more frequent use of the Grafham to Affinity import. Some of the proposals for the reservoir also include a transfer to Cambridgeshire. Thus, the South Lincolnshire reservoir could affect supply across the entire Eastern portion of the Arc.
3. The proposed reservoir near Abingdon would store either 75,000Ml or 150,000Ml to supply 150Ml/d or 300Ml/d for use by Thames and Affinity Water. This reservoir is primarily a source of water for growth in London. However, if that growth instead is redirected to the Arc it could be used much in the same way as the Severn to Thames transfer, but without the drawback of impacting United Utilities. However, proposals for this reservoir have been repeatedly turned down and it has become a controversial issue.
4. The Beckton wastewater treatment plant, the largest in Europe, has proposals that it could recycle up to 300Ml/d of water for redeployment back into London's water network. As with the Severn to Thames transfer, this would free up more water in the River Thames and could be made to impact the entire Western portion of the Arc. The disadvantage of this scheme is that it is incredibly expensive, possibly as expensive as desalination.
5. A transfer of water from the River Trent to Rutland reservoir (the second largest reservoir in the UK) of 200Ml/d has been proposed in the past. The combination of a transfer directly to such a large reservoir is highly favourable in terms of making the most of water in the Trent. It would supply Northamptonshire, Bedfordshire and Luton/Affinity Water (via the same mechanism as the South Lincolnshire) with the added benefit that no new reservoir needs to be constructed. This proposal has currently been shelved due to water quality and environmental concerns. However, we suggest that all options above are large civil infrastructure projects that may be found to be subject to these problems. A possible remedy to these concerns would be to treat the water before release into the reservoir (effectively treating it twice). While this would be expensive, it may still prove cheaper than options such as wastewater reuse, desalination or possibly even construction of a new reservoir (the Abingdon reservoir has been suggested to cost £1bn, while a new water treatment works costs in the order of £100 million).

We analysed changing demand for water in the Arc and the impacts of climate change on water availability. Population growth will increase demand for water (which may be offset by reductions in per capita demand), whilst climate change is making the Arc region warmer (on average) and is making rainfall less predictable.

Our analysis examined the strategic water supply infrastructure options being considered by water companies. The results are presented in terms of the annual probability of water shortages.[45]

Figure 47 shows the annual risk of water shortages for each WRZ in the 2030s. The results are given for each of our scenarios, with two levels of action around demand management and leakage reduction (either current levels of demand and leakage, or the more ambitious reductions that water companies are now targeting) and for a range of water supply infrastructure options.

All large infrastructure options under consideration in this region have some impact in reducing risk. The Thames Water options (Severn Thames transfers, Abingdon reservoir, Beckton re-use) benefit the SWOX WRZ, while the Anglian Water options (Trent-Rutland transfer, South Lincolnshire reservoir) mainly benefit Ruthamford North, with Ruthamford South achieving some gains.

In general, reservoirs are more effective than transfers, since during droughts when the transfer is needed, the transfer source is also likely to be under stress and have less water available. There are significant environmental impacts of both transfers and reservoirs. While more expensive, the Beckton effluent re-use scheme (Thames Water) is the most effective option at reducing risk since its reliability is less dependent on weather conditions than reservoirs or transfers.

Figure 47 suggests that the best approach may be to focus on demand management and leakage reduction, options which have very few unintended consequences (environmentally or otherwise) and prove to be the most effective means at reducing risk of water use restrictions. The proposed levels of leakage reduction and demand management are already incorporated in water companies' future plans, but it is difficult to predict how many of these will be able to be implemented in practice. Note that the indication that Severn Thames transfer increases risk in Ruthamford South under 'New Settlements 30k' may be due to the choice of visualisation rather than being a significant result.

The different dwelling/population scenarios for the Arc impact the risk of restrictions to varying degrees. The western area (SWOX) is much more sensitive to water demand changes in London (not examined here) than it is to any of the Arc scenarios. Ruthamford North has increased in risk under all scenarios, but 'Expansion' in particular. Ruthamford South has increased in risk under all scenarios, but 'New Settlements' in particular. The 'Unplanned' scenario has the lowest increase in risk relative to the baseline because population growth is lower overall and is spread across the Arc rather than being concentrated in any particular centre(s).

Thames Water can manage the risk of water shortages for any Arc scenario by either fulfilling their plans for leakage reduction and demand management, or by extensive water reuse at Beckton (a 300Ml/d project), which would be one of the largest schemes of its kind in the world.

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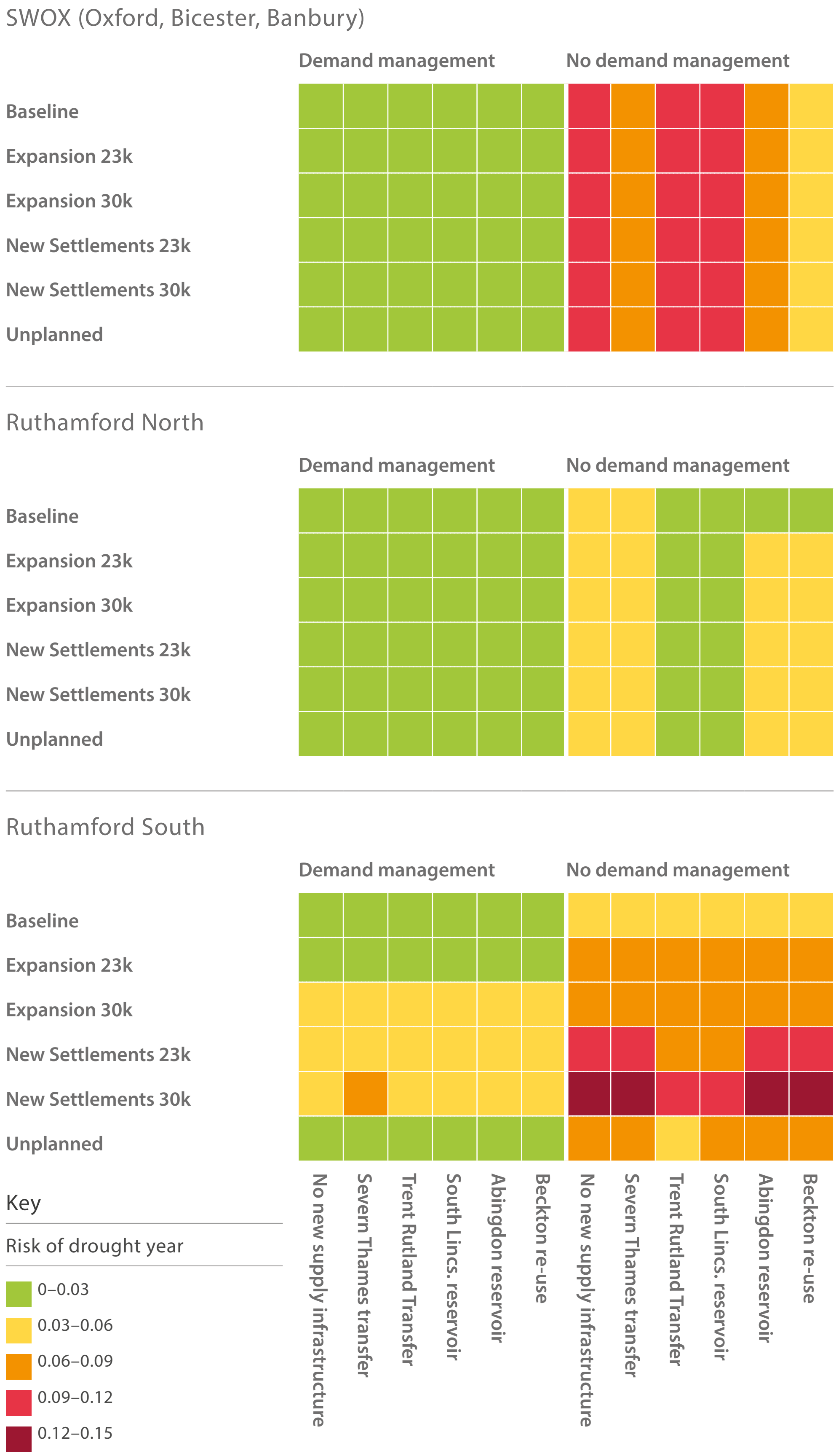
45 We consider the more severe Level 3 and Level 4 restrictions on water use.

Figure 47: Risk of water shortages in the 2030s for different Arc scenarios, levels of demand management and water supply infrastructure options.



Anglian Water's plans can manage the risk of water shortages for any Arc scenario other than the 'New Settlements' scenario, which would increase the risk of water shortages. The South Lincolnshire reservoir is highly effective at mitigating risk in the Ruthamford North WRZ, but Ruthamford South would still be subject to increasing risk if the Arc goes ahead. If, for example, a transfer from the reservoir to Ruthamford South were to be implemented, then the 'New Settlements' scenario may become viable.

7.4 Digital communications

The fifth generation of cellular technology (5G) will provide significant improvements over the previous generation (4G), by providing enhanced capacity, as well as reduced latency. Mobile Network Operators around the world have begun to roll-out new 5G infrastructure.

While many 5G use cases are proposed, the main current use is enhanced mobile broadband. Significant supply-side changes are expected in how mobile networks deliver data services, including the deployment of new spectrum bands utilising more efficient 5G technologies and increased network densification via the deployment of Small Cells.

Whereas in 4G, Macro Cells mainly provided wide-area data access, there is some expectation that with 5G there will be millions of Small Cells covering much smaller areas with much higher capacity. While Macro Cells may serve a radius of up to 30km in remote rural areas, Small Cells are expected to serve anywhere from 1-2km down to 200 metres in the densest urban settings. As 5G technologies are still evolving, we lack analysis of the implications and policy ramifications of Small Cell deployment strategies. Figure 48 provides a stylised example of a Macro Cell coverage area, with a high density of Small Cells operating within this area to provide localised high capacity hotspots.

There are a range of views on the potential impact of 5G, ranging from optimistic[46] to conservative.[47] While impressive capacity can be achieved with 4G LTE and 4G LTE-Advanced technologies, the mobile industry will need to move to 5G and other technology generations over the long-term in order to help reduce the cost per bit associated with data transfer, as well as addressing a broader range of new use cases and industries. The Average Revenue Per User (ARPU) has either been static or declining in many major economies over the past decade, particularly in Europe, and globally ARPU fell by 1% in 2018.[48]

46 International Telecommunication Union (2015). 'IMT Vision – Framework and Overall Objectives of the Future Development of IMT for 2020 and beyond.

47 Webb, W. (2016). The 5G Myth: And Why Consistent Connectivity Is a Better Future.

48 GSMA (2018). 'GSMA Intelligence Global Data'.

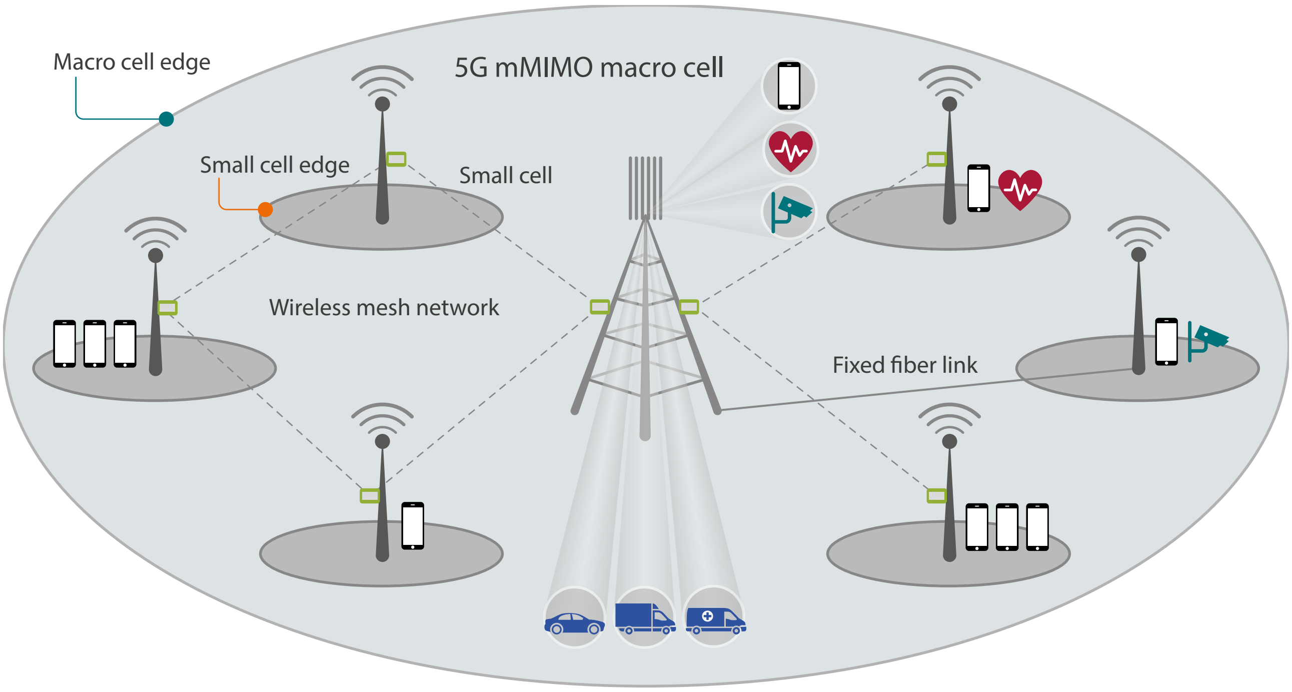


Figure 48: Key features of 5G infrastructure.

One of the first infrastructure assessments of 5G was the UK Government's Connected Future report.[49] Analysis has estimated it would take until 2027 for the majority of the population to be covered by 5G,[50] with the UK government now having adopted this target in both Ofcom's Connected Nation report and in the UK's Future Telecoms Infrastructure Review.[51,52]

Throughout the UK coverage issues still exist in many areas, with only 76% of premises receiving an indoor 4G signal from all operators, and only 64% of the geographic area.[53] Past UK spectrum coverage obligations include 90% population coverage on the 3G bands including 900, 1800 and 2100MHz, and a 98% population coverage requirement on the 4G LTE 800MHz with 90% confidence at indoor locations with a downlink speed of not less than 2Mbps, while 2600MHz has no coverage obligation.[54]

There has also been a focus on broadband access. Currently, 94% of homes and businesses have access to Superfast Broadband via Fibre-To-The-Cabinet (FTTC), meaning at least 30 Mbps can be achieved.[55]

49 National Infrastructure Commission (2016). 'Connected Future'.

50 Oughton, E.J., and Z. Frias (2018). 'The Cost, Coverage and Rollout Implications of 5G Infrastructure in Britain'. Telecommunications Policy, The implications of 5G networks: *Paving the way for mobile innovation?* 42 (8): 636–52.

51 Department for Digital, Culture, Media & Sport (2018). Future Telecoms Infrastructure Review.

52 Ofcom (2018). 'Connected Nations 2018: UK Report'.

53 Ofcom (2018). 'Connected Nations Update: October 2018'.

54 Cave, M., and Nicholls, R. (2017). The use of spectrum auctions to attain multiple objectives: Policy implications. *Telecommunications Policy*, 41(5–6), 367–378.

55 Ofcom (2018). 'The Communications Market 2018'.

In 2017, the National Infrastructure Commission instructed Tactis & Prism[56] to estimate the costs of future digital communications infrastructure, producing an estimated capital expenditure cost for UK-wide full Fibre-To-The-Premises (FTTP) of £28 billion. While over the past decade the focus has generally been on delivering full coverage of FTTC, the next decade will aim to deliver FTTP. The National Infrastructure Commission[57] has currently set an ambitious target of all premises having access to FTTP by 2033.

Given there are a range of demand-side, supply-side and policy factors affecting the roll-out of digital infrastructure, the following questions are addressed in this report:

1. What will future mobile data growth look like?
2. Which 5G infrastructure strategies are most cost-efficient?
3. How do 5G economics affect the delivery of this infrastructure to urban, suburban and rural areas across the Arc?
4. What is the cost of full FTTP across the Arc?

7.4.1 Demand assessment

The two key demand drivers for mobile data are (i) the number of users in an area, and (ii) per user data throughput rate. Residential population scenarios are taken at a Postcode Sector level to estimate the number of users in each area.

Per user data demand is taken from Cisco forecasts,[58] which project significant growth in UK mobile traffic over the coming years at 38.5% Compound Annual Growth Rate (CAGR). Data demand has recently risen from approximately 0.2GB per month in 2012 to 1.9GB per month in 2017,[59] and the adoption of unlimited data plans is likely to have a substantial impact on future data growth. The average user data rate is taken from these forecasts to give the traffic demand in gigabytes per user per month in Britain, from which the busy hour individual demand is estimated. For further information on this method, see Oughton et al.[60] and Appendix A.

Figure 49 illustrates the data demand results, beginning with the monthly per user data consumption (A) and population growth (B). Data consumption per user increases significantly over the time period. Monthly consumption is approximately 5GB per user in 2020, over 10GB by 2023 and almost 20GB by 2030.

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56 Tactis and Prism (2017). Costs for digital communications infrastructures: a cost analysis of the UK's digital communications infrastructure options 2017-2050.

57 NIC (2018). National Infrastructure Assessment: an assessment of the United Kingdom's needs up to 2050.

58 Cisco (2017). 'VNI Mobile Forecast Highlights Tool'.

59 Ofcom (2018). 'The Communication Market 2018'.

60 Oughton, E.J., Z. Frias, T. Russell, D. Sicker, and D.D. Cleevely (2018). Towards 5G: Scenario-Based Assessment of the Future Supply and Demand for Mobile Telecommunications Infrastructure. *Technological Forecasting and Social Change* 133 (August): 141–55.

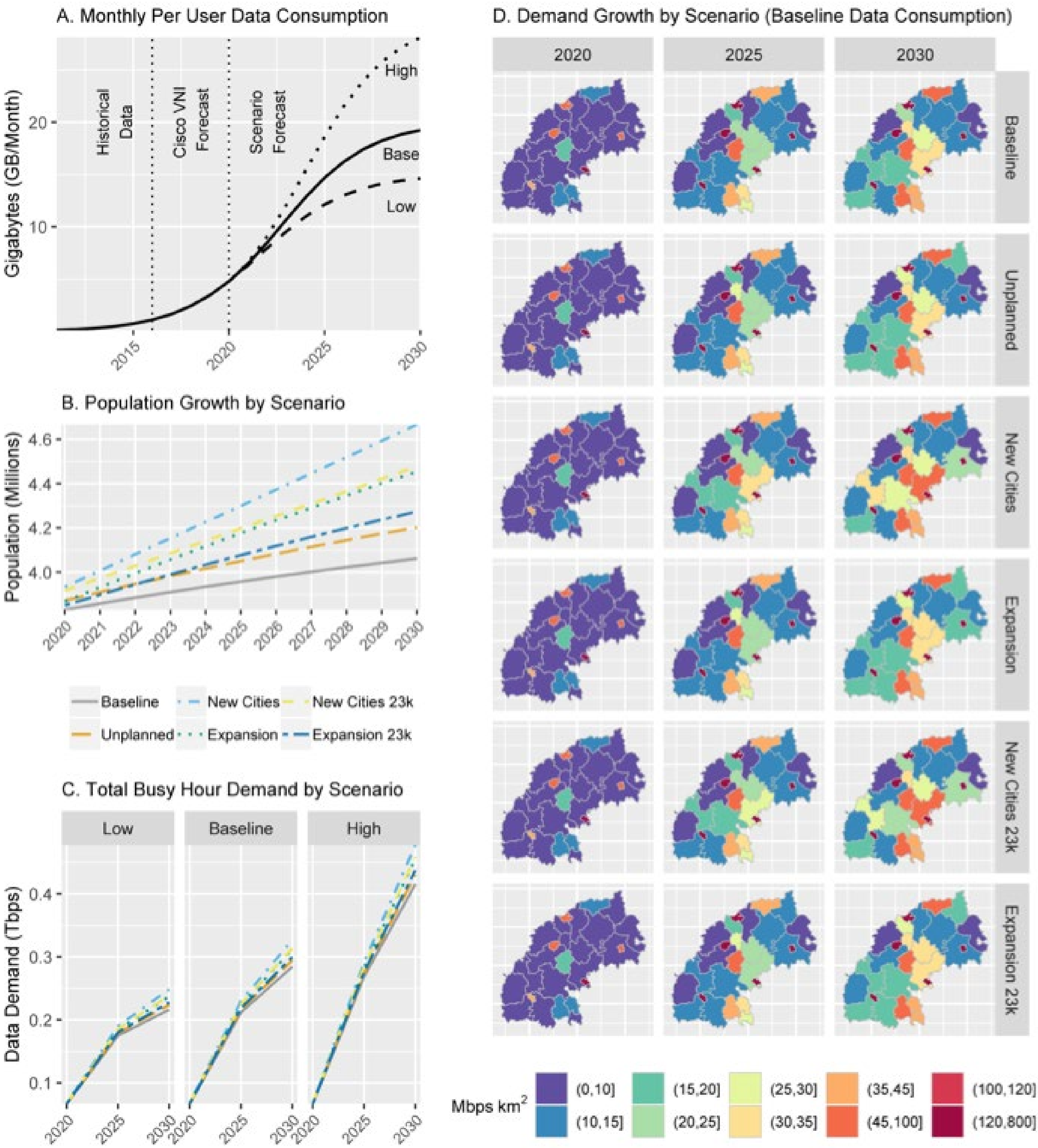


Figure 49: Demand results.

Population growth in the Arc corridor varies by demographic scenario, ranging from below 4 million people in all scenarios in 2020, to almost 4.1 in 2030 in the Baseline, and over 4.6 million by 2030 in New Settlements. Both New Settlements 23k and Expansion reach over 4.4 million people by 2030, whereas Unplanned and Expansion 23k reach 4.2 million people by 2030.

The total data demand in the busiest hour of the day is visualized by scenario in (C), where the Baseline evolved from below 0.1Tbps in 2020, to approximately 0.3Tbps in 2030. Whereas the low growth scenario reached over 0.2Tbps in 2030, the high growth scenario saw demand increase to over 0.4Tbps.

The key message from these results, however, is that the difference in the population growth by scenario has only a marginal impact on the total data demand, because of the very rapid increases already taking place in per user data demand.

Plot (D) visualises the spatial demand for each scenario. In 2020, demand is generally below 10 Mbps per km2, except in urban areas such as Luton (165 Mbps per km2) and Cambridge (62 Mbps per km2). In the Baseline, by 2030 all urban areas exceed 120 Mbps per km2 and many less populated rural areas see demand increase above 15 Mbps per km2. In contrast to the Baseline, the largest spatial differences in other scenarios reflect spatial development patterns. In the Unplanned scenario we see increases in South Oxfordshire in the West and Fenland in the East, whereas in the Expansion 30k and Expansion 23k scenarios there are additional demand increases in South Cambridgeshire and Bedford. The New Settlements 30k and New Settlements 23k scenarios lead to increased demand to the North and East of Oxford in Cherwell and Aylesbury Vale respectively, as well as in North of Luton in Central Bedfordshire.

7.4.2 Capacity assessment

A variety of different 5G deployment strategies are tested. It is logical to expect that if 4G LTE is not already present on a site these spectrum bands are added first along with any necessary fibre backhaul upgrades. Moreover, we expect that operators want to maximize the reuse of existing brownfield Macro Cell sites to reduce investment costs when densifying the existing network.

The four strategies tested are as follows. No Investment represents a case where no new infrastructure capacity is deployed to meet demand. Spectrum Integration enables the hypothetical operator to add new frequencies (700 MHz, 3.5 GHz and 26 GHz) to multi-carrier base-stations on existing brownfield Macro Cell sites. Small Cells involves the deployment of greenfield Small Cell sites and associated backhaul. Finally, the Spectrum and Small Cell strategy allows the options involved in the Spectrum Integration strategy to be first deployed, followed by Small Cells, should the capacity be required.

Figure 50 visualizes the results for user capacity and cost. Firstly, the mean cell edge user capacity represents the data transfer rate a user is guaranteed to achieved 90% of the time at the furthest point away from the closest cell site. Under the No Investment strategy, the guaranteed capacity would drop from over 9.4 Mbps to under 8.8 Mbps per user over the study period, which is typical for wide area coverage using 4G. In the Spectrum Integration strategy this rate would increase from 18.2 Mbps in 2020 to 61.5 Mbps per user in 2030, contrasting with the Small Cell strategy where the rate increased from 43.0 Mbps to 108.5 Mbps. In the mixed Spectrum and Small Cells strategy, capacity ranged from 19.2 Mbps in 2020 up to 72.5 Mbps in 2030.

The difference from the Baseline is then presented by scenario and strategy. Under No Investment, we can see the largest decrease in capacity is in the New Settlements scenario, although the decrease is only approximately 1 Mbps. This capacity difference is larger in the Spectrum Integration strategy, where the user rate drops by 6 Mbps from the Baseline in the most extreme New Cities scenario. In the remaining Small Cell, and Spectrum and Small Cell, strategies, the dynamic is broadly the same, except that new capacity is brought online between 2025-2028 to meet larger demand in the New Settlements, Unplanned and Expansion scenarios.

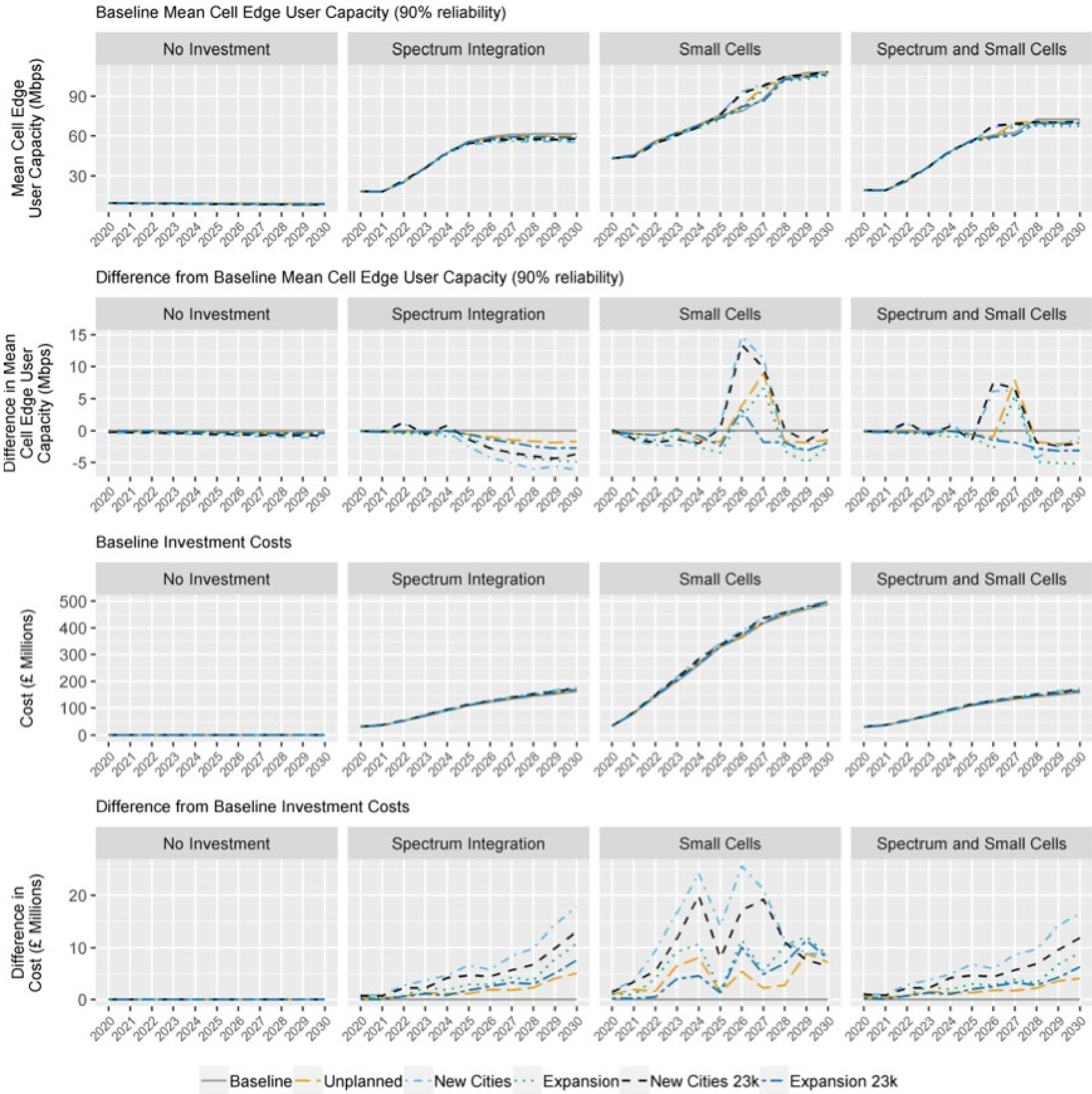


Figure 50: Performance of 5G infrastructure deployment strategies.

In terms of the Total Cost of Ownership, the Spectrum Integration strategy was approximately £160 million, with the Spectrum and Small Cells strategy in the same range at £158 million. In contrast, the Small Cell strategy was much more costly, with all scenarios costing approximately £490 million to cover the Arc, so roughly three times more expensive. When comparing the difference across scenarios, the cumulative cost for Spectrum Integration and Spectrum and Small Cells is approximately £15 million more in the New Settlements case when compared to the Baseline, with the Unplanned and Expansion scenarios being approximately between £5-10 million more expensive than Baseline.

Figure 51 breaks down these costs based on the type of urban-rural settlement pattern. While we do not see a vast difference between the scenarios, there are significant differences between the strategies. The Spectrum Integration, and Spectrum and Small Cell strategies, carry out upgrades in urban, suburban and rural areas, earlier in the study period, and maintain an even spread of investment across settlement patterns, even from 2025 onwards. These strategies represent an incremental deployment approach, where new capacity is delivered expediently to meet growth demand. This contrasts with the Small Cell strategy, where investment targets urban and suburban areas earlier on in the study period, slowly rolling out to rural areas later in the study period. This reflects the fact that greenfield small cells are more expensive than merely adding spectrum to existing brownfield sites, so it takes longer for small cell deployments to be delivered. On the other hand, enough capacity is delivered in urban and suburban areas that once they have small cell deployments, capacity far outstrips demand, therefore the model does not need to return to carry out further upgrades (unlike in other strategies).

Finally, Figure 52 illustrates investments made by deployment decision. The shape of the investment curves is the same as in Figure 51, however, the breakdown of cost by item can be read in tandem, helping us to understand infrastructure decisions by settlement type. For example, in the Spectrum Integration and Spectrum and Small Cell strategies, some 4G LTE upgrades still need to take place in the first year of deployment, but the remaining upgrades focus on delivering 700 MHz across urban, suburban and rural areas. Some areas receive upgrades to 3.5 GHz, although these take place in urban areas to meet very high demand.

In the Small Cell strategy, some 4G LTE upgrades still take place, but mainly spending is dominated by the deployment of greenfield 5G small cells. In contrast, the Spectrum and Small Cell strategy is like the Spectrum Integration strategy, with a small number of small cells being deployed in areas where existing spectrum has not met demand. This is an important finding, as it suggests demand can generally be met using existing spectrum integrated onto brownfield Macro Cell sites.

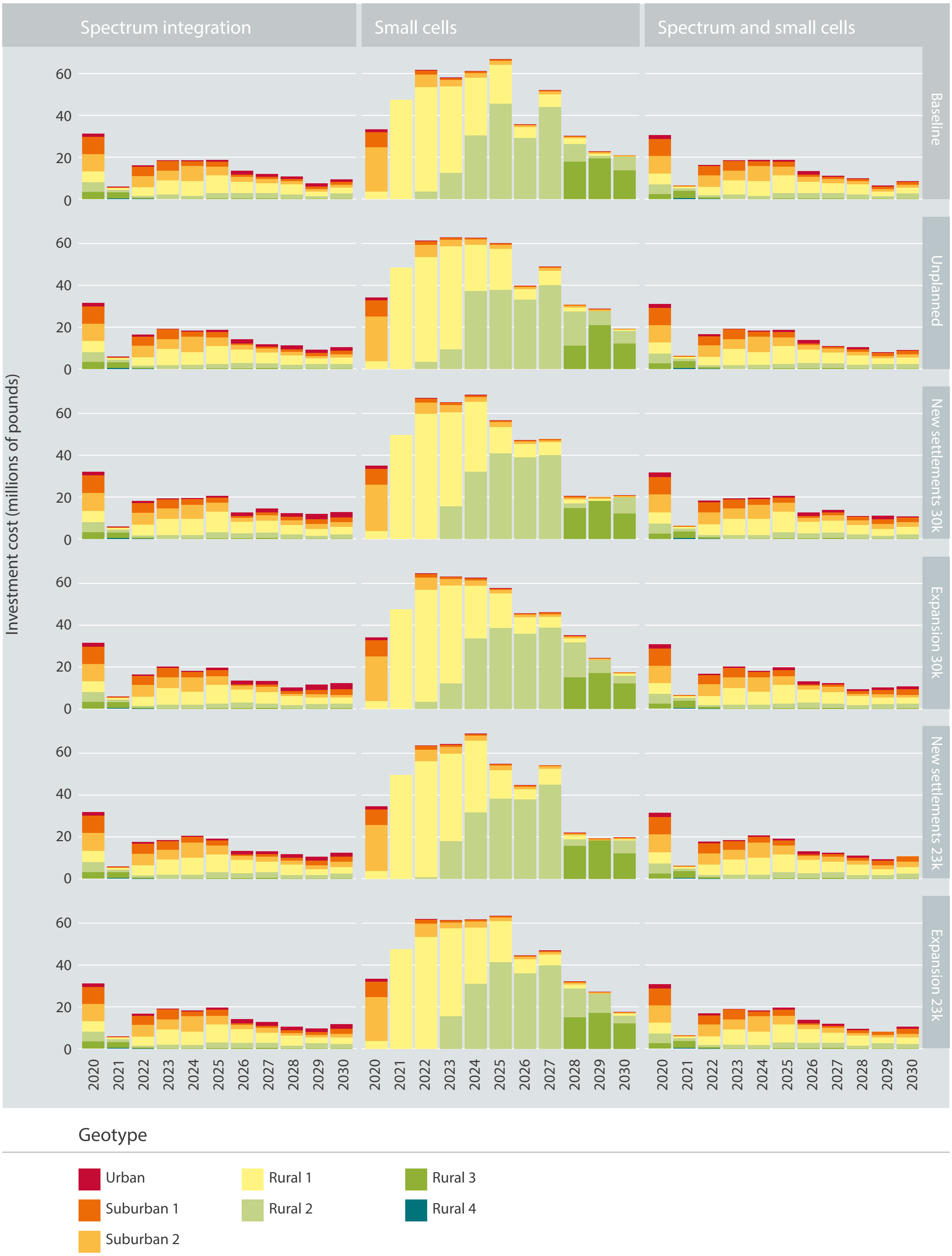


Figure 51: Investment broken down by settlement type.

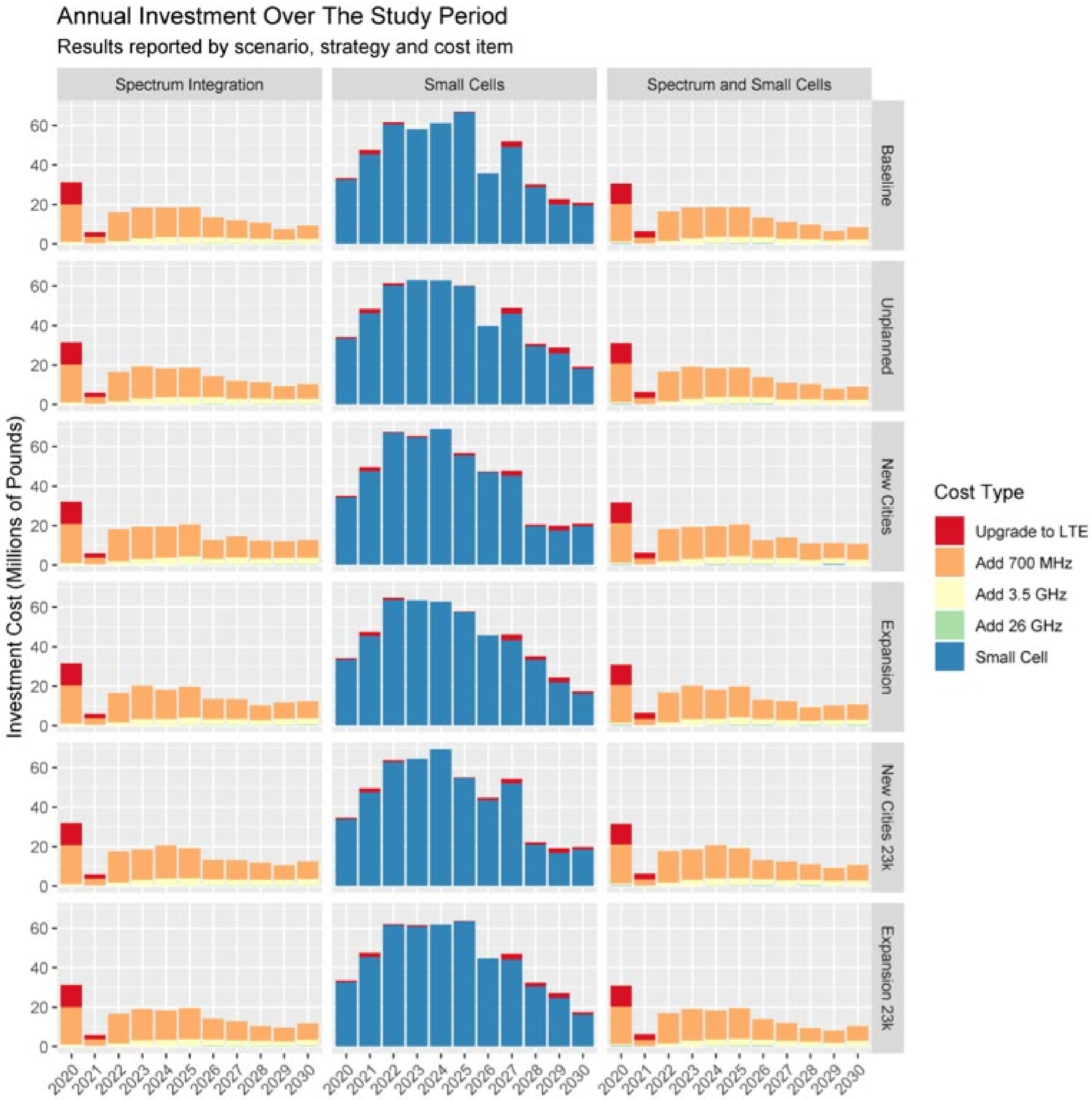


Figure 52: Investment broken down by deployment decision.

7.4.3 Fibre-to-the-Premises

The fixed broadband modelling assesses the cost of Fibre-to-the-Premises based on density of premises in Output Areas under different urban development scenarios. The model used here relies on network cost information from the report produced by Tactis & Prism for the NIC.[61] More information on the density-based geotyping approach is provided in Appendix A.

61 Tactis and Prism (2017). Costs for Digital Communications Infrastructure: A Cost Analysis of the UK's Digital Communications Infrastructure options 2017–2050.

The two infrastructure deployment strategies explored are a full greenfield approach where no existing infrastructure is used (100% FTTP No Reuse), and a brownfield approach which reuses all existing underground ducting and overhead pole assets (100% FTTP Reuse).

The cost of delivering full Fibre-To-The-Premises in the Arc by 2050 ranges from £1.59-2.34 billion depending on the Arc scenario and strategy. Costs are lower if existing underground ducting and overhead poles are reused, as shown in Table 8. Ofcom have been taking measures to ensure existing infrastructure is open for fibre deployment, therefore the likelihood is that reuse will take place in most circumstances, and lead to lower costs.

Table 8: Estimated costs of delivering FTTP broadband in the Arc (for all premises built by 2050)

	Baseline	Unplanned	Expansion	New Settlements
Costs of 100% FTTP with infrastructure reuse	**£1.59 billion**	**£1.66 billion**	**£1.85 billion**	**£1.87 billion**
Costs of 100% FTTP with no infrastructure reuse	**£2.05 billion**	**£2.12 billion**	**£2.33 billion**	**£2.34 billion**

7.4.4 Discussion

Population growth has a relatively minimal impact on the total data demand, which is instead driven by the exponential growth in per user data consumption. This growth is predominantly a consequence of the consumer desire for streaming more and more on-demand video while on the go.

The spatial variance which did arise resulted from the settlement patterns from different scenarios. For example, the New Settlements scenarios saw greenfield development between the existing urban settlements within the Arc corridor, which will require new greenfield infrastructure to be deployed to meet future demand.

In terms of capacity, the Small Cell strategy provided the highest overall cell edge gain in per user 4G and 5G data access rates, at almost twice the provided capacity over other strategies, reaching an average of 120 Mbps per user by the end of the study period in 2030. The Spectrum Integration strategy by 2030 only achieved approximately 60 Mbps per user in comparison. The Spectrum and Small Cell strategy was only marginally better in comparison however, delivering roughly 75 Mbps per user by 2030.

The cost of delivering this capacity is a different matter, however. For example, the Small Cell strategy might have provided the largest uplift in user capacity, but the deployment approach was more than three times more expensive when compared to other options, cumulatively spending up to £500 million by the end of the study period. In comparison, the Spectrum Integration strategy, as well as the combined Spectrum and Small Cell strategy, both reached a cumulative cost of approximately £150 million by 2030.

The hybrid strategy of deploying both new spectrum on brownfield Macro Cell sites, and Small Cells in the areas of highest demand, proved to be the best, as there was a slight cost saving over a strategy based purely on brownfield Spectrum Integration, while also providing marginally better capacity gains, particularly in the later years of the study period.

Many local authorities are undertaking their own small cell deployment strategies, mainly by leasing street furniture for a set period (e.g. 30 years) to a single neutral host operator.

In this analysis, small cells were found to provide significant capacity, but at a substantial cost. On the one hand, it would be cheaper to adopt a strategy which utilizes brownfield Macro Cells as much as possible, as generally the analysis found that 5G spectrum deployed on these assets could meet demand. This argument could be further justified by the fact that new 5G technologies not tested in this analysis could be deployed on Macro Cell sites to provide superior capacity if required, such as 'Massive Multiple-In, Multiple-Out' (Massive-MIMO).

On the other hand, there is an argument that moving to small cells, particularly in those areas of highest demand, such as urban centres, is a future-proof solution. In this analysis we only focused on the use case of Enhanced Mobile Broadband which serves those applications which are less sensitive to disruptions to the received signal from the cell site transmitter. However, other 5G use cases that focus on ultra-low latency and high reliability applications, may only be achievable by deploying a small cell network as it dramatically increases the probability of achieving direct line-of-sight in street canyons and other environments where Macro Cells could be blocked by 'clutter' such as buildings.

Additionally, although the simulation model utilized here was sophisticated in many aspects, the model was ultimately static and did not contain people or vehicle movements. Mobility matters because the gathering of people in a single area can dramatically increase the demand placed on the cellular network, leading to congestion. This needs to be an area for future research.

There are many ramifications for policy decision makers, particularly local, regional and national planners who often:

i. Control the deployment of new cellular sites via planning or zoning methods.

ii. Have influence over public street furniture (e.g. lampposts or bus stops) which could mount Small Cell hotspots.

iii. May own or control underground access ducts, or overhead poles, which could deploy fibre optic cable.

Firstly, cells mounted higher up are more likely to provide direct line-of-sight and better radio wave propagation. The higher a cell is mounted, the larger the probability a user's smartphone has of receiving good quality signal, thus achieving more efficient data transfer.

Planners should take seriously the effective provisioning of new cell sites, which may include (i) allowing taller greenfield masts to be erected, or brownfield sites to be extended upwards, or (ii) potentially allowing new cell sites to be located on top of government buildings.

Secondly, being able to mount small cells on street furniture is also very important because it may not be viable to erect thousands of new bespoke masts on every street. Which means there needs to be a co-operative business arrangement between the public infrastructure owner, and a market operator who can deploy and manage the necessary infrastructure.

Finally, local governments often own or have control over local management systems, such as highway traffic management systems. Existing cabling either exists in underground ducts, or via overhead poles, both of which could be used to help reduce the costs of fibre deployment to connect new cells back into the internet. Fibre density is essential for 5G deployment to ensure the desired capacity and latency requirements can be met. It is always cheaper to reuse existing assets, rather than to dig new ducting, for example. Local government should consider the various underground assets that they own, and whether access could be granted to private sector fibre providers, either for some monetary rental value, or in some beneficial transactional relationship where an operator gains access in return for connecting economically unviable areas.

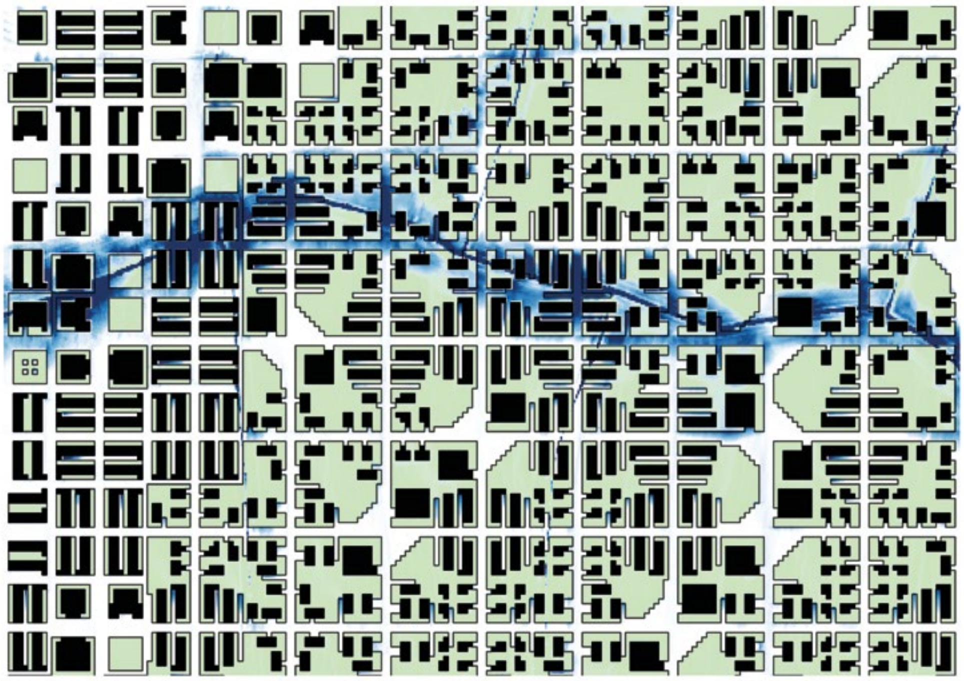
A key caveat is that while such policy options could prove to be a potential revenue source, there is an important trade-off. Excessive rents would mean (i) there may be less funding available for rural infrastructure projects which are in much need of reliable internet connectivity, and (ii) could deter further investment. Hence, local governments need to balance the amount of revenue they may want to generate from publicly owned assets, against their commitment to fostering the digital economy in their local area, and providing near-ubiquitous, reliable internet connectivity.

7.5 Urban drainage

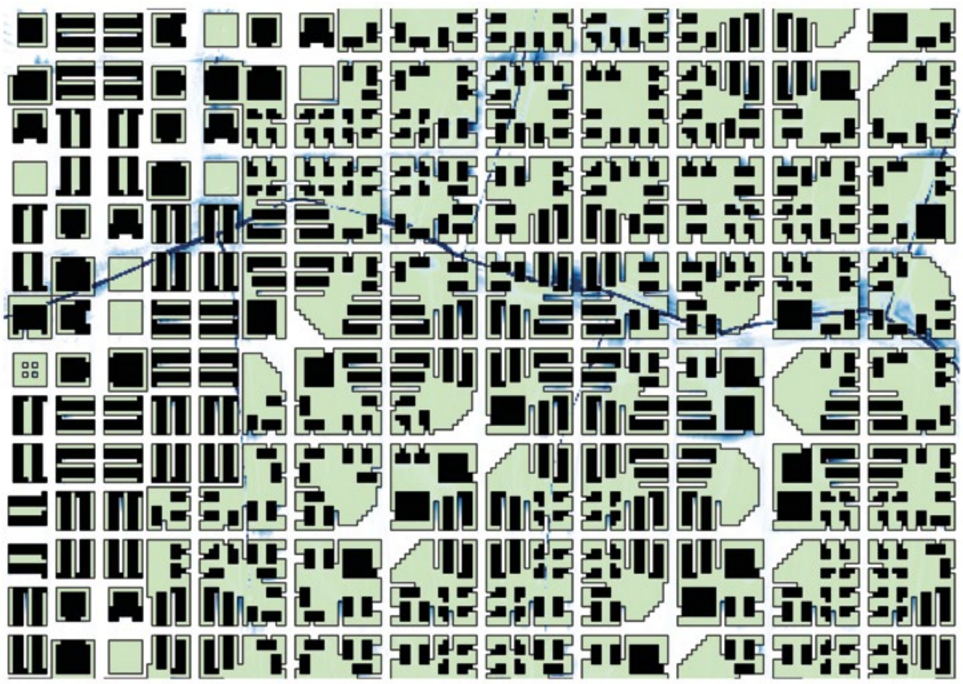
New conurbations require an effective urban and wastewater drainage strategy, allowing cost-effective and efficient use of sewer networks and Waste Water Treatment Plants (WWTPs). Conventional urban drainage design in the UK has traditionally relied on urban runoff being conveyed through the sewerage network mixed with wastewater. That results in unnecessary treatment of large volumes of storm water at WWTPs and the widely recognised problem of sewer overflows during storms.

This ITRC-MISTRAL research applies a flexible and powerful methodology for defining an urban configuration and then modelling its drainage, allowing a range of realistic representations of surface drainage to be assessed. We consider the economic and physical impacts of alternative drainage strategies, primarily separation of the networks (clean and foul) and use of Blue Green Infrastructure. This work assesses these strategies using new simulation methodologies for (a) generating realistic urban and drainage layouts at the full town scale and (b) estimating the cost and performance of drainage solutions.

a) No sewer network



b) Sewer network



Key

Water depth (m)

- 0
- 0.1
- 0.2
- 0.3
- 0.4

Landuse

- Buildings
- Green areas

Figure 53: Flood depth maps for a 100 year design storm showing the effects of (a) inset roads (b) conventional drainage density.

The flood depth resulting from the different models shows some interesting features (see flood depth maps in Figure 53). Firstly, the surface flows are primarily governed by the natural topography, but heavily modified by the road network acting as channels. Secondly, the introduction of a sewer network at standard drain spacing has a major benefit in reducing flooding. This is further improved by introducing a higher density network.

A flexible and powerful methodology has been developed for firstly defining an urban configuration and then modelling its drainage, allowing a range of realistic representations of surface drainage to be assessed.

The drainage efficiency and associated flood risk of the development can be estimated by simulation using this methodology, leading to optimisation by assessing a range of design options including blue green infrastructure and sewer separation.

This work is ongoing. The next steps are to extend the idealised drainage system to include the sewer pipe network. Simple costing methods will then be applied to estimate: (a) costs of pipe network and inlet drains for different levels of service; (b) costs and benefits of multiple decentralised WWTPs relative to single WWTP and associated pumping; and (c) costs of Blue Green Infrastructure solutions to achieve same levels of service.

7.6 Urban form

The residential urban forms typologies and their spatial characteristics are classified based on centre, urban, suburban, and rural within the whole Arc area with 71% general Random Forest (RF) model accuracy. The results of this classification is used to forecast the likely combinations of residential urban form typologies and the number of dwellings for the densification of different brownfield lands within the LADs, taking into account the future number of dwellings and the characteristics of surrounding urban forms. The location and area of brownfield land for each LAD are available from the National Housing Federation. The results of classification for the whole Arc and the generic characteristics of each class (centre, urban, suburban, and rural) are shown in Figure 54 and Tables E1-E4 (Appendix E). The RF model accuracy tables and the variable importance are presented in Appendix E (Fig. E1, and Tables E5-E7).

Assuming the brownfield lands planned by the LADs are meant only for residential development (and thus do not include other land uses including commercial, offices, etc.), the number of dwellings that can be accommodated through densification for each brownfield land in the Arc are estimated. Here we provide results for four density scenarios (very high, high, medium, and low) and three cases for each scenario (for further details see Tables E8 (standard development) and E9 (green development) in Appendix E). The estimated total number of dwellings in the Arc by 2050 is around 2 million and estimated total (cumulative) areas of brownfield land in the Arc is 3826 hectares (National Housing Federation data). The densification results are presented in Table 9 and explained for the very high-density scenario.

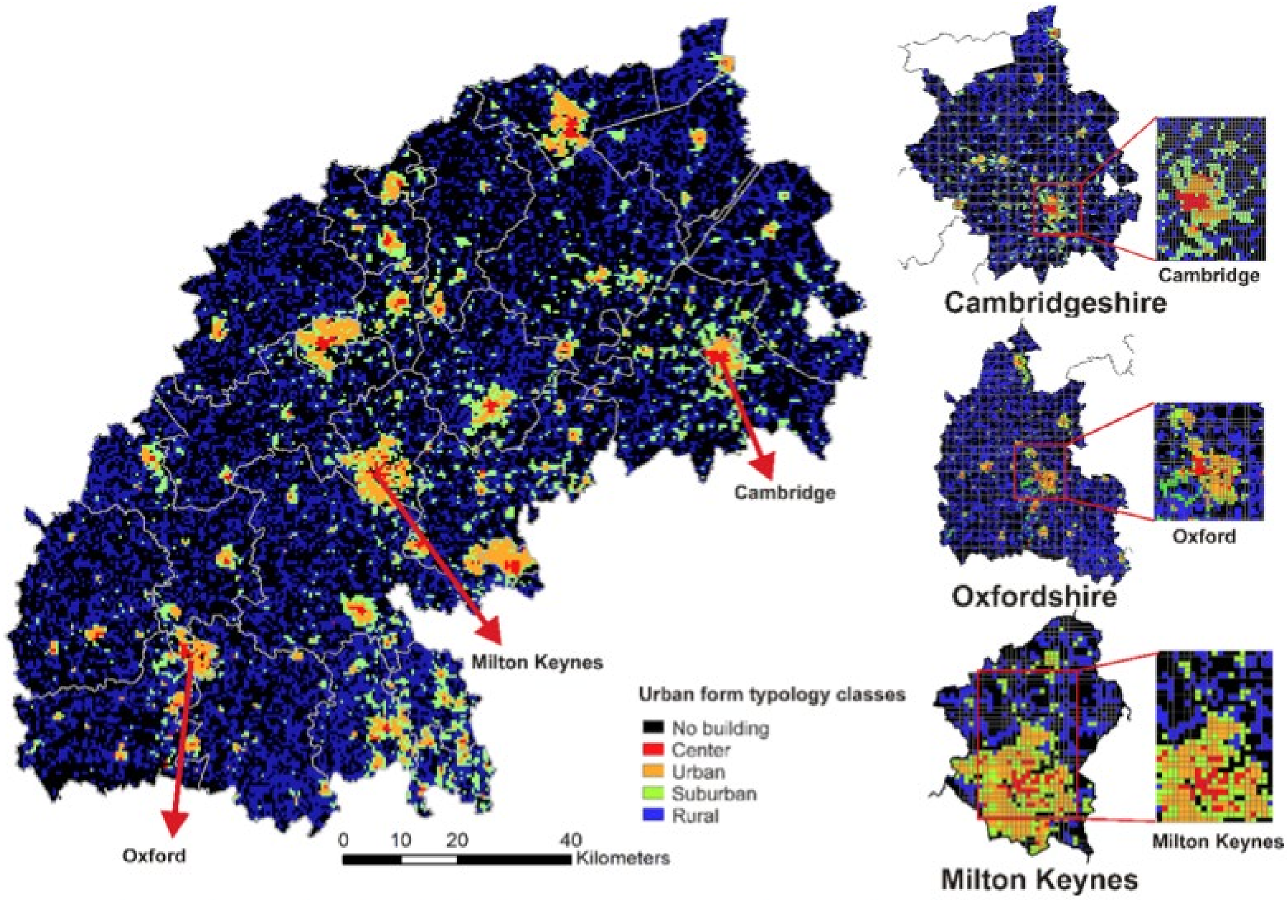


Figure 54: The classification of residential urban forms based on centre, urban, suburb, and rural within the whole Arc area for the tiles of 500m × 500m. The generic characteristics of each class (centre, urban, suburban, and rural) is presented in Tables E1-E4 in Appendix E.

Table 9: Results of densification for the very high and high density scenarios						
	Very-high density scenario			High density scenario		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Number of Dwellings	490,800	691,538	843,292	138,307	381,306	624,305
% of Dwellings	24%	34%	41%	7%	19%	31%
Future km2 land	36	74	55	508	163	85
	Medium density Scenario			Low density scenario		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Number of Dwellings	103,731	295,825	487,919	40,340	115,256	190,173
% of Dwellings	5%	15%	24%	2%	6%	9%
Future km2 land	726	217	121	1874	600	387

The number of dwellings varies for very-high density scenario in the three cases from about 490 thousand, to 691 thousand, and to 843 thousand. These numbers corresponding to 24%, 34%, and 41%, respectively, of the new projected dwellings for 2050 for the Arc as a whole which can be accommodated through densification. In addition, again for very-high density scenario, the total square kilometre land that is needed for the new settlements in the Arc by 2050, varies from 36 km2, to 55 km2, and to 74 km2.

7.7 Green infrastructure

We have mapped the ability of natural capital assets in the Arc to deliver 18 ecosystem services, using a habitat-scoring method (see Appendix E). Examples of the output maps for selected services are shown below.

7.7.1 Food production

Food production is a key service in the Arc region, with extensive Grade 1 and 2 agricultural land on the rich soils of Fenland and the other eastern districts as well as on the lower slopes of the Ridgeway in southern Oxfordshire (Figure 55). Although the Arc only covers 8.8% of England, it contains 20.5% of England's Grade 1 agricultural land, 15% of Grade 2 and 9.5% of Grade 3 (Figure 56). Loss of this high quality agricultural land would be expected to lead to an increase in food imports, with potential environmental and socio-economic impacts.

The basic score for arable fields, horticulture, improved (fertilised) grassland and intensive orchards is 10 out of 10 for this service. Allotments score 7, semi-natural (rough) grassland scores 6, wood pasture and traditional orchards score 5, marshy grassland scores 4, and very rough grazing (bog or heath), domestic gardens and wild food sources such as woodlands and hedgerows (for gathering berries or mushrooms) all score 1. However the scores for intensive farmland are strongly modified by the multiplier for agricultural land class. For an arable field, the normalised score would be 10 for Grade 1 land, 8 for Grade 2, 4.4 for Grade 3, 2.2 for Grade 4 and 1.6 for Grade 5. These multipliers are based on the estimated difference in productivity (in tonnes wheat per ha) plus a further uplift to reflect the versatility of Grade 1 and 2 land.

Figure 55: Natural capital scores for food production, based on habitat and Agricultural Land Class.

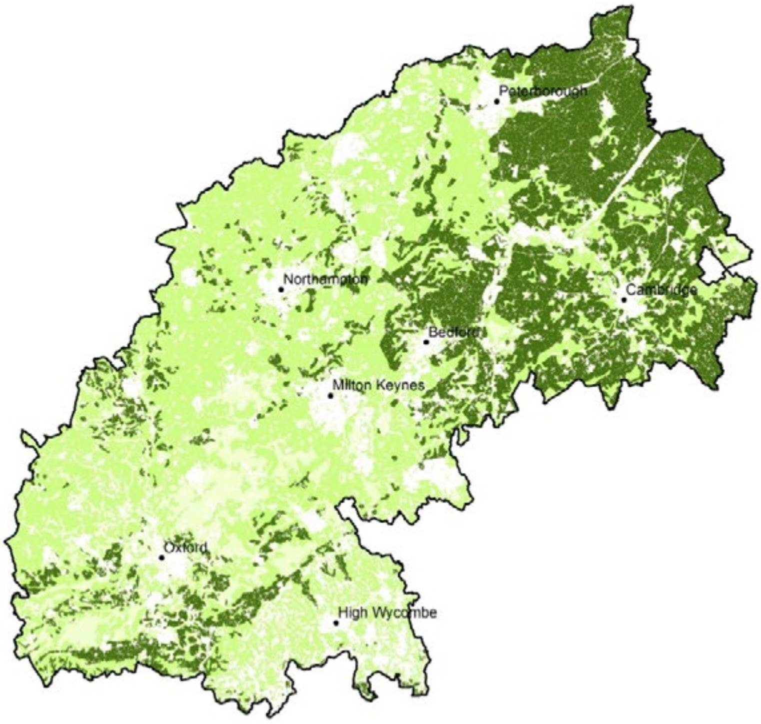
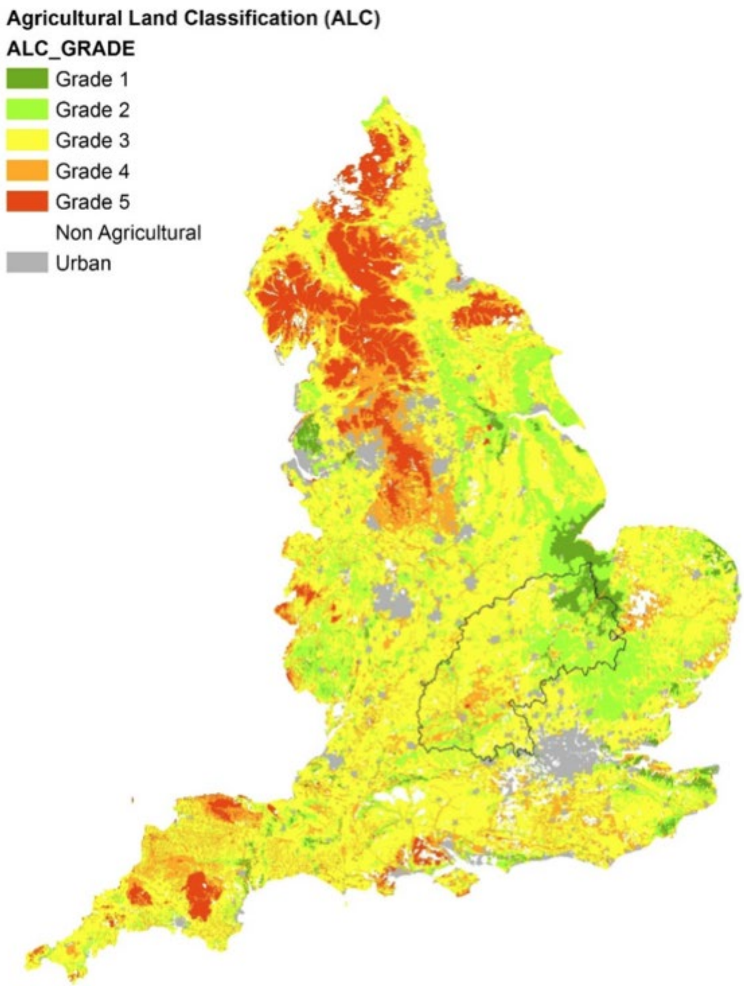


Figure 56: The Arc contains a high proportion of England's best and most versatile agricultural land.



7.7.2 Water supply

Any permeable surface will either allow groundwater recharge or (if there is no connection to a groundwater body) will allow rainwater to infiltrate into the ground where it can then slowly recharge local surface water supplies via horizontal sub-surface flow. Rivers, lakes and reservoirs score the maximum 10 for water supply, as water can be abstracted directly. We do not currently distinguish between water bodies that flow into reservoirs and other surface water bodies. Bogs and wetlands are particularly good at storing water, and therefore also score 10. For other habitats, we allocate higher scores to types of land cover that permit groundwater recharge. For example, semi-natural grassland is expected to have a good soil structure allowing infiltration and groundwater recharge, so scores 9. More compacted grassland such as improved grass and amenity grass scores 7, as some rainwater will run off into drains and straight out to the river network rather than infiltrating. Arable land also scores 7, though in reality some crops are water-hungry and also many fields are under-drained, sending any rainwater straight out to the river network, so this score should probably be lower in those cases. Trees tend to intercept rainwater and it can then be lost through evapotranspiration. Coniferous plantations are often water-hungry, and so these score 1. However, broadleaved woodland loses its leaves in winter when rainfall is highest, and also tends to improve soil structure and infiltration. It therefore scores 3, and scrub (which uses less water) scores 4. Sealed surfaces score zero, although if they are connected to a sustainable drainage system (SuDS), e.g. leading to a retention or detention basin, they may play a role in recharge. We do not yet take this into account in the scoring system but this could be done in future.

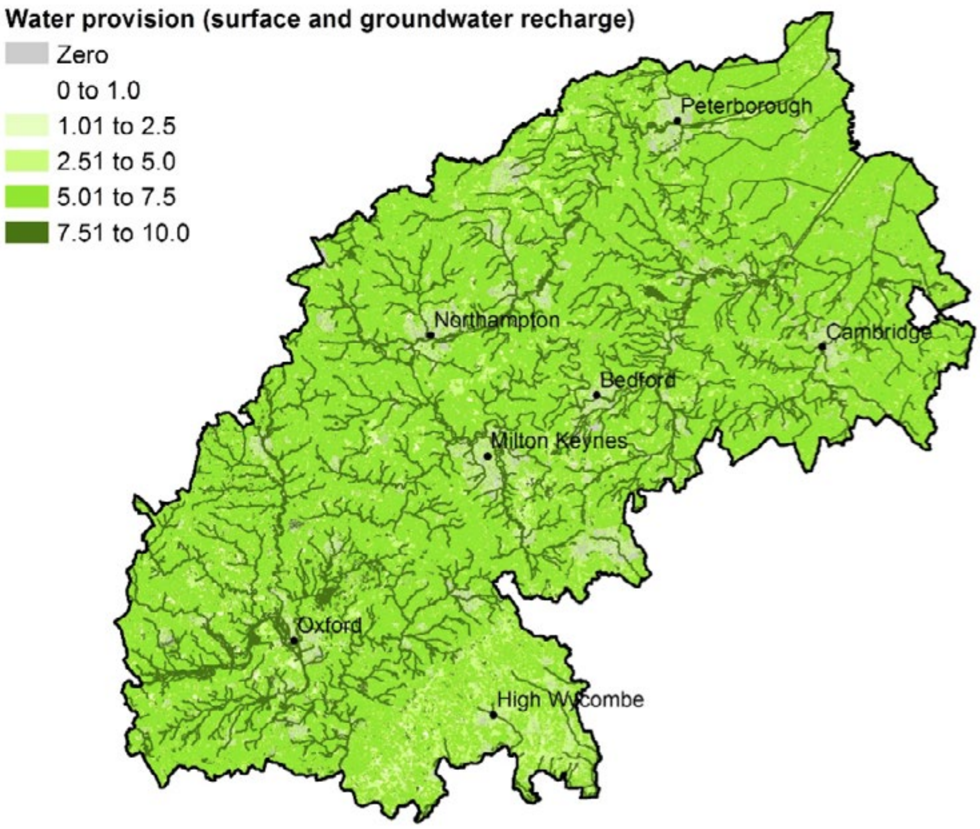


Figure 57: Ability of habitats in the Arc to contribute to water supply (via direct surface water abstraction or indirectly via groundwater or surface water recharge).

Most of the Arc scores medium-high for water supply (Figure 57), with higher scores along the river network, lower scores for woodland, and zero scores in built-up areas. This emphasises the role that both farmland and semi-natural grassland play in enabling groundwater recharge. However, as noted above, it is possible that the high score for arable land may be an overestimate.

7.7.3 Interaction with nature

'Interaction with nature' includes formal or informal activities such as birdwatching or plant-spotting, random encounters with wildlife, and a general feeling of being 'connected to nature', all of which have benefits for health and wellbeing. This service can be delivered in any habitat where wildlife and nature can be encountered, including urban green spaces. More abundant and diverse wildlife is likely to be found in natural or semi-natural areas and/or in protected areas, but domestic gardens often have more wildlife than surrounding areas if the region is intensively farmed. While areas with high biodiversity can be good places for people to interact with nature, there can also be conflicts such as when dogs disturb nesting birds or hunt small mammals.

We assign higher scores to the most distinctive semi-natural habitats, such as semi-natural broad-leaved woodland, hedgerows, semi-natural grassland, freshwater and wetlands, and lower scores to habitats with less biodiversity interest.

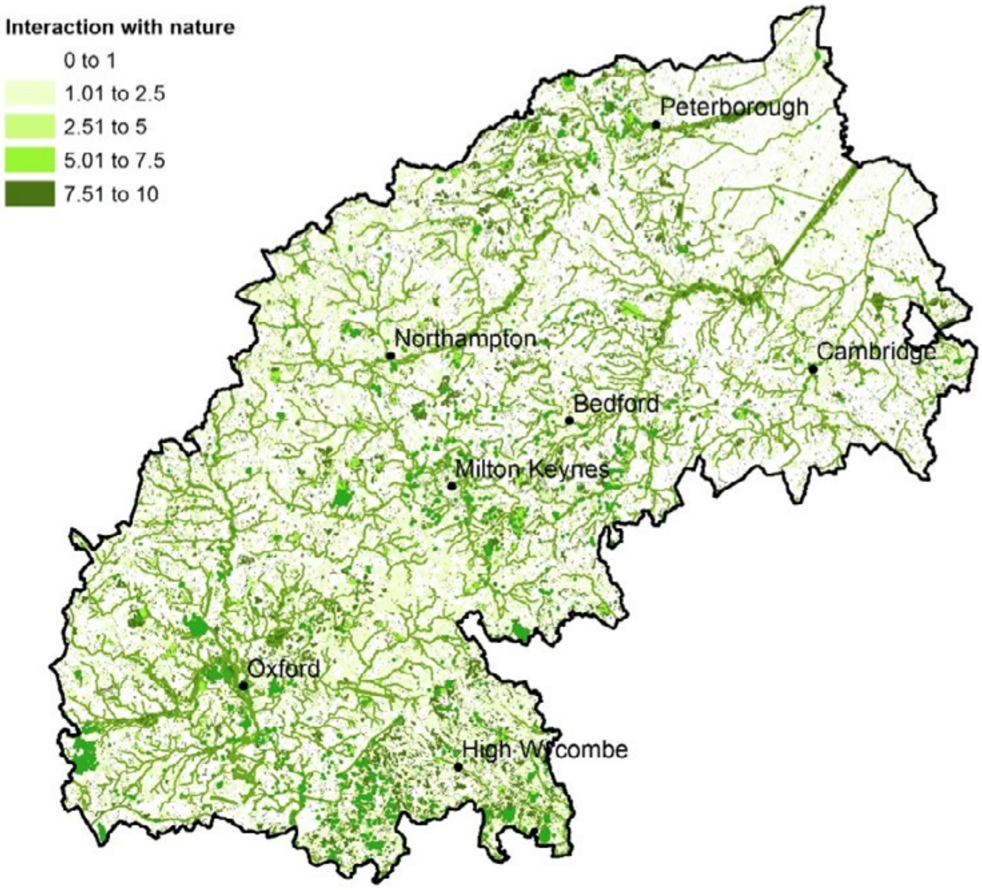


Figure 58: Ability of habitats in the Arc to provide opportunities for interaction with nature, including the river network.

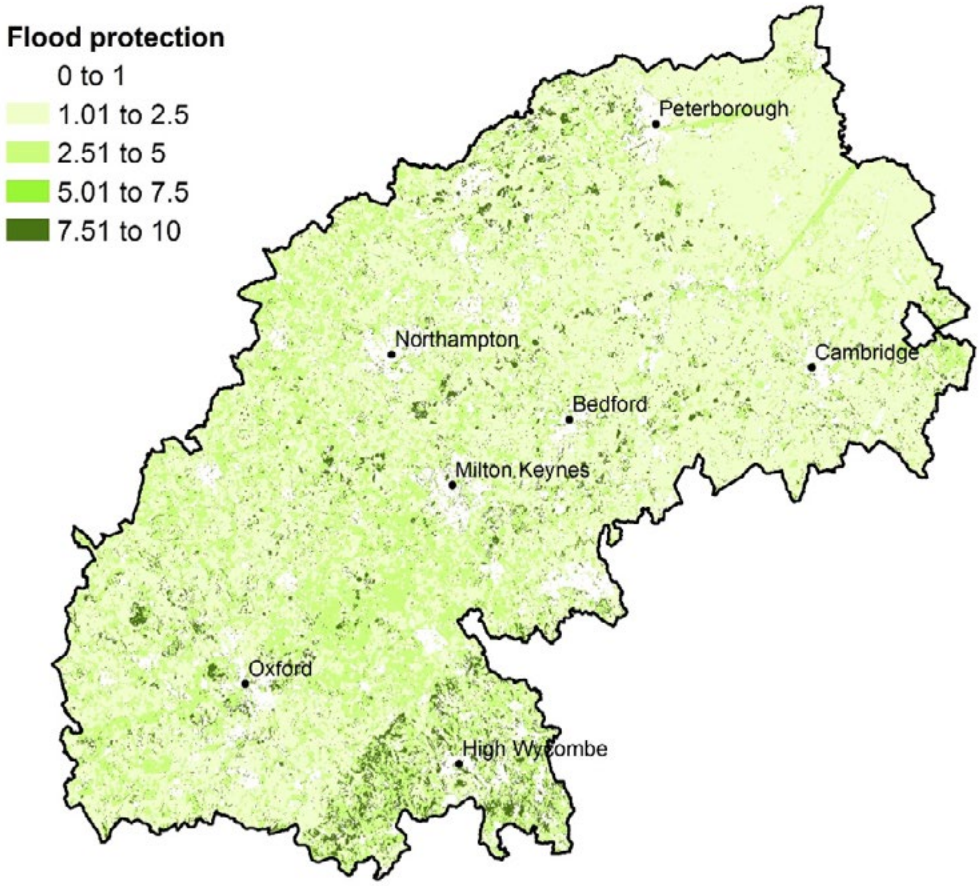
We also apply a multiplier for areas with nature designations, including Local and National Nature Reserves, Special Areas of Conservation, Special Protection Areas, Important Bird Areas, Ramsar sites, RSPB reserves, SSSIs, Ancient woodlands and (in Oxfordshire only) Local wildlife sites (including proposed sites) and Road verge nature reserves. The multiplier is 1.1 if one of these designations applies, 1.15 if two apply and 1.2 if three or more apply. We map ancient trees and the river network as a separate layer.

The map shows that the dominance of intensive agriculture in the Arc limits its value for allowing people to interact with nature. On the scale of the whole Arc, the areas that stand out include the Chiltern woodlands, the river valleys and large parks and nature reserves. However, zooming in to a local level reveals the value of many smaller areas of semi-natural habitats and urban green spaces.

7.7.4 Flood protection

Vegetation intercepts rainfall and absorbs moisture from the soil, while permeable soils enable rainfall to infiltrate into the ground. This can reduce run-off after heavy rainfall, reducing the risk of flooding. Woodland has the highest score for the service of flood protection, with coniferous woodland scoring highest (as it is in leaf all year round). Semi-natural grassland is assumed to have a good soil structure, and therefore scores more than more compacted habitats such as amenity grass, improved grassland and arable fields.

Figure 59: Ability of habitats in the Arc to protect against flooding.



The ability of land in the Arc to reduce flood risk is mapped in Figure 59. As with most of the other regulating services, the few high-scoring areas are woodlands such as the Chilterns in the south, but the lack of woodland cover results in a generally low score. There are therefore considerable opportunities for natural flood management measures such as tree-planting to contribute to reducing flood risk.

7.7.5 Combined score

Although we have developed maps for 18 different services, it can be useful for decision-makers to see a combined map. In theory, scores for different services cannot be added together or averaged because they are not in common units. Therefore we show the 'maximum' score for all services instead. Figure 60 shows the maximum score for regulating and cultural services in shades of green, but distinguishes the areas with high scores for food production in a different colour (orange). This is because most areas tend to deliver either food production or a bundle of other regulating and cultural services – not both, as this tends to be mutually exclusive. The map does not include the service of water supply / groundwater recharge, as this would make most of the map bright green and thus obscure the detail of the other services (see Figure 57).

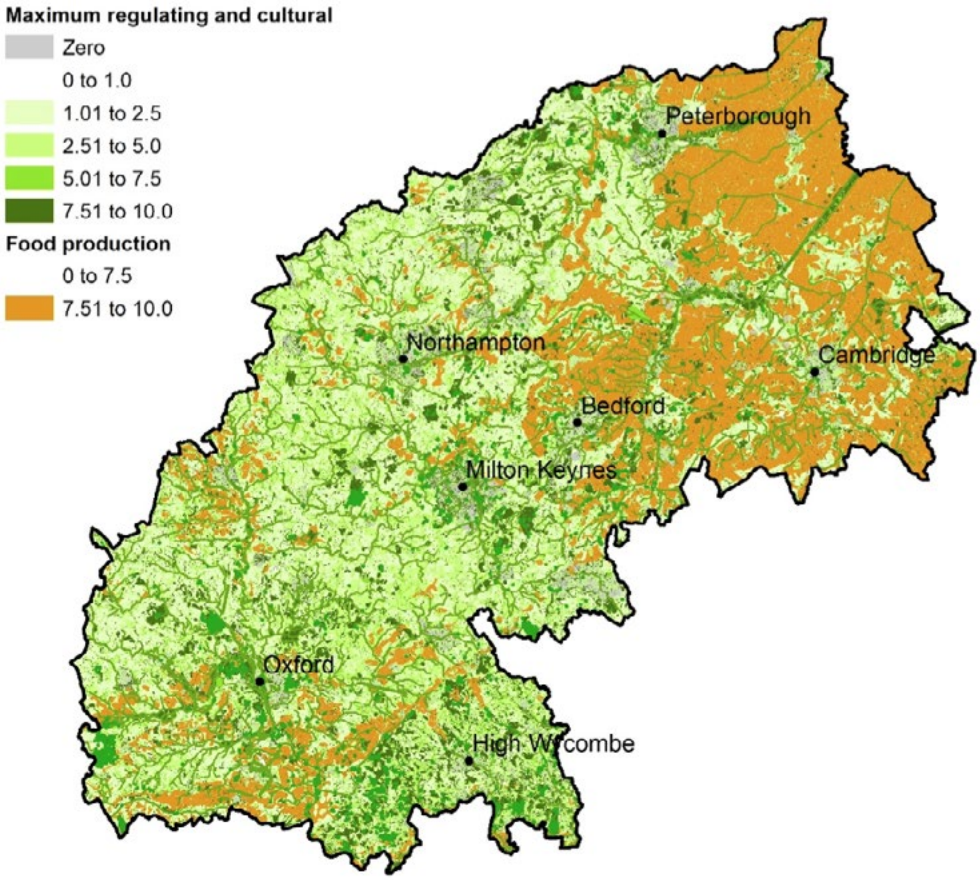


Figure 60: Maximum score for regulating and cultural services (shades of green) or food production (orange).

We can compare the natural capital maps against the different scenarios assessed in the MISTRAL study. Preliminary results to indicate the relative impact of the four development scenarios on selected ecosystem service scores are shown in Figure 61.

The charts add up the scores (multiplied by the area of each polygon) within the areas allocated for new development under each scenario, to show the services and natural capital assets that are at risk of loss. It is likely that not all of this natural capital value will actually be lost as some habitats could be partly retained, and new green space could be built into the development. However the charts do allow comparison of the relative impacts of the scenarios.

The top left chart (a) shows the difference in the areas covered by new development under each scenario. The top right chart (b) indicates the area of 'high value natural capital assets' that are at risk of being lost to development under each scenario. Four different criteria are used to select the assets:

i. areas with a medium score (at least 5 out of 10) for any of the regulating or cultural services;

ii. areas with a high score (at least 7.5 out of 10) for any of the regulating or cultural services;

iii. multi-functional areas, that have at least one high score (as for ii)), but also have an average score over 5 out of 10 for all the regulating and cultural services and water supply;

iv. high scoring areas (at least 7.5 out of 10) for food production – in practice, this equates to Grade 1 and 2 agricultural land. This shows particularly high potential losses of good quality farmland under the new settlement scenario.

The middle chart (c) shows the total score for the supply of each ecosystem service by habitats within the area that would be developed under each scenario. However, as the scenarios each deliver a different number of dwellings, the comparison does not indicate which development pattern has the lowest impact. Therefore the lower chart (d) shows the score per hectare, to enable a more meaningful comparison.

The over-riding factor is the development footprint, with chart (c) showing that the Baseline scenario (20,000 ha of new development) has the lowest impact, followed by the Unplanned scenario (30,000 ha), the Expansion scenario (48,000 ha) and then the New Settlements scenario (58,000 ha). However, chart (d) shows that the potential loss of services per hectare is generally slightly higher for the Unplanned scenario as it has fewer environmental constraints.

An example is shown in Figure 62, where the area modelled as being a potential new settlement is mainly on relatively low value natural capital land, but overlaps with some high grade farmland, semi-natural grassland and woodlands, and a network of rural footpaths. Careful design would be needed to preserve the high value assets within this zone, and create new assets to serve the needs of future residents. In the next stage of work we will seek to develop a 'Green Vision' scenario to explore the extent to which it is possible to minimise impacts on natural capital through compact development that preserves existing high value assets such as trees, hedges and semi-natural grassland while creating new high quality green infrastructure in new developments.

Figure 61: Potential loss of ecosystem services within the development zone for each scenario.

7.7.6 Green infrastructure summary

In the Arc, food production is a major service but the dominance of intensively farmed agricultural land means that the semi-natural habitats providing other essential ecosystem services are sparse and fragmented. Particularly in the Unplanned scenario, where development is unconstrained, there are risks of further depletion and fragmentation of important natural habitats. This threatens undermining quality of life for current and future residents and fails to exploit opportunities such as cost-effective flood protection, carbon storage, active travel routes and health benefits.

If the vision of a green Arc is to be realised, development must be carefully planned to preserve and integrate existing natural capital assets, create new green corridors for people and wildlife, and follow garden town principles for any new developments. The maps presented here can be used as a first step towards natural capital planning, but further improvement and refinement is needed – incorporating detailed local information and stakeholder knowledge.

Planners need to be aware of gains and losses under different scenarios. All land provides some benefits for people – even relatively low-grade agricultural land. If less food is produced, it must be produced somewhere else instead and the environmental impacts could be greater. This emphasises the need to minimise land take, keeping developments compact but building in enough multifunctional green space and green corridors to maintain ecological integrity and provide services for people. Even with a 'Green Arc' vision in place, it will be challenging to achieve net gains in natural capital in line with government aspirations, given the scale of the development envisaged. The priority is to ensure that gains and losses are transparent, to inform stakeholder discussions around the synergies and trade-offs of different development scenarios.

This work is ongoing, and further analysis and refinement will be carried out in future.

Figure 62: Example of a new settlement in the Mistral scenario, shown against high value natural capital assets.

8. Summary

This report demonstrates how the ITRC-MISTRAL modelling suite NISMOD can provide independent systems-based analysis of the implications of future change, and provide new insights into the implications of the major policy themes related to population change and new transport infrastructure. The analyses are based around the development of the road and rail networks between Oxford and Cambridge, and three contrasting growth scenarios for new dwellings within the Arc. The future of the Arc is likely to be a combination of different types of development, but for ease of comparison we have examined the cases whereby development is focused either on (i) Expansion of existing settlements; (ii) in New Settlements; or (iii) is Unplanned so happens in a haphazard way across the Arc.

The allocation of new dwellings and population for each Arc scenario are modelled by assessing development suitability using a set of constraints and attractors, with future employment demand met by a combination of urban densification, urban fringe developments, new hinterland locations, and at significant new developments based around prospective transport hubs. While Expansion of existing conurbations is likely to impact on protected greenbelt areas, careful planning could allow development of New Settlements, while still protecting greenbelt land and other important habitats in the Arc.

The Expressway initially delivers some time savings for longer road journeys, such as between Oxford and Cambridge, but the fastest route choices more locally tend to remain on existing roads, depending on the origin and destination. For all growth scenarios, higher population implies higher levels of congestion, and while the planned road expansions and developments initially generate time travel savings, congestion levels and travel times will increase in the longer term if steps are not taken to manage demand for road transport and transfer passengers onto other modes of transport including rail and 'active travel' (walking and cycling). Notwithstanding high population growth, uptake of electric vehicles would result in a sharp decrease in carbon emissions and local air pollution in the longer term, although electrification will substantially increase electricity demand.

The vision of a carbon neutral Arc is achievable, given the current trends in generating increasing amounts of electricity from renewable sources and the potential for increased uptake of renewables within the Arc. The greatest challenge to achieving a carbon neutral Arc is how to heat new and existing buildings without using fossil fuels. We have examined a 'multi-vector' energy solution, which incorporates local heat networks, green gas and widespread use of electric heating. This enhances resiliency and operational flexibility compared to a heating solution that relies entirely on electricity; however, it is hindered by increased systems complexity, and high capital costs. The most cost-effective route to decarbonisation of heating may be transitioning to heat pumps, resistive heating and electric boilers, and running these on decarbonised electricity. However, there are barriers to such a future, such as the potential disruption to households during retrofitted installation, relatively high capital costs of low-carbon heat technologies, and potential gaps in engineering training and human capacity.

A campaign to raise awareness of such technologies may help increase public confidence and uptake. It will be much more cost-effective to incorporate these technologies from the outset in the new buildings within the Arc, but developers should also consider improvements to energy efficiency and insulation to reduce the energy requirements of heating.

Population change only has a minor impact on demand for 5G infrastructure, which is largely driven by the changing nature of per user data consumption, particularly for on-demand video. Significant supply-side changes are expected in how mobile networks deliver data services, and a combination of deploying new spectrum bands utilising 5G technologies and increased network densification through Small Cells may be the most cost-effective and reliable means of delivery in dense urban areas. There are further cost efficiencies to be gained through coordinated planning of both fixed and mobile digital communications, particularly when building and maintaining other infrastructure sectors.

The Arc is served by four water companies, and if these companies are able to deliver on their plans for demand management and leakage reduction, future per capita demand for water will decrease, but population growth in the Arc is projected to increase total water use in the long-term. Without new infrastructure to improve supply, the risk of restrictions on water use doubles by 2050. These risks can be somewhat mitigated through new reservoirs (as proposed by Anglian Water) and effluent reuse schemes (as proposed by Thames Water at Beckton in East London).

The scenarios considered are transformative. Baseline population growth takes the Arc from 3.7 million people in 2015 to 4.4 million in 2050; the higher growth Expansion and New Settlements scenarios consider up to 5.4 and 6.1 million people respectively by 2050. Strategies to significantly reduce the carbon emissions from heat and transport require sweeping technology transitions. Population growth drives increases in water demand despite per-capita reductions while the generally drier near-future climate scenarios contribute to increased risk of water use restrictions. Full-fibre and 5G broadband must prioritise coverage if they are to meet future expectations of digital connectivity.

The Arc region is not isolated. Population change, economic growth and their implications for infrastructure services in the Arc have wider impacts on a regional and national context. Some of the housing pressure within the Arc comes from demand in London and the South-East. Part of the motivation for the road and rail improvements comes from the need to move freight more effectively between the East of England, South West England and South Wales. North-south transport flows also affect congestion on the major roads in the Arc. Resilience to drought in the SWOX water resource zone is linked to the Thames system and London. Transmission-connected electricity generation across the country affects the cost, reliability and carbon intensity of electricity consumed within the Arc.

Changes in one sector have effects in others. Rapid vehicle electrification would reduce transport emissions and increase electricity demand from transport, while demand-side management (including from grid-connected vehicle batteries) is effective in reducing peak demand.

Existing urban areas have opportunities for densification and challenges to upgrade, adopt or retrofit technologies. New developments present opportunities to build to the highest standards of energy efficiency, introduce heat networks, lay ducts for fibre and design sustainable drainage, but also challenges to preserve green corridors, design liveable places and build urban environments that can adapt and last.

In conclusion, this analysis of the Arc shows the benefits of an integrated analysis of infrastructure development, including sectoral interaction. The development and analysis of consistent scenarios including a range of possible urban forms illustrates the diverse ways the Arc may develop. Key interactions between sectors such as growing electricity demand for transport are also apparent as well as wider consequences of the Arc development such as in water supply.

This report shows how ITRC-MISTRAL modelling capabilities can be applied in a regional context. All this new information and these insights can inform the ongoing debate about how the Arc will proceed and the key policy decisions and actions that need to follow. The ITRC-MISTRAL modelling suite NISMOD is continuing to be developed for national and regional application within the UK and around the world.

Appendix A: Model descriptions

The following sections give detailed descriptions of the models used in these analyses.

Much of the model and integration code is available online under open-source licenses within the NISMOD GitHub organisation. [62]The scenarios which combine dwellings, employment, GVA and population are produced by the arc-scenarios[63] workflow. The system-of-systems model, nismod2[64] configures those scenarios and other parameterisations to run the energy, transport, water and digital infrastructure models using a simulation modelling integration framework, smif.[65]

1. Spatial Interaction Models of Internal Migration (SIMIM)

Population scenarios have been developed using SIMIM to model variations in internal migration which may be driven by changes in the attractiveness of the Local Authority Districts (LADs) of the Arc. The dwellings completion scenarios provide changes to the rates of dwelling completions for each LAD in the Arc to 2050. The economics scenarios provided by Cambridge Econometrics define employment and GVA for each sector, for each LAD in the Arc. Accessibility to employment via road and rail is calculated using current and future transport infrastructure (consistently with the Arc transport infrastructure assumptions) and used in each scenario except for the baseline. Baseline population and household projections for the UK are provided by the Office of National Statistics 2016-based principal population projection (mid-year estimates for 2015 and 2016, sub-national projections up to 2040, national projections disaggregated to LAD from 2040 to 2050), accessed using the ukpopulation[66] package.

The rationale for the SIMIM[67] model is to take the ONS principal population projection, baseline internal migration data (from the 2011 census) and attractiveness factors that may govern migration (accessibility to employment, GVA and housing). The first step is to construct a spatial interaction model of internal migration from the baseline data. Then the scenarios are applied to change the attractiveness factors of each region, the model is reapplied, and a modified migration O-D matrix is generated.

62 National Infrastructure Systems Model on GitHub, https://github.com/nismod

63 Russell, T. (2019). Arc scenarios v1.0.0. Available online: https://github.com/nismod/arc-scenarios doi: 10.5281/zenodo.3529473

64 Russell, T., Usher, W. et al. (2019). nismod2 v2.2.0. Available online: https://github.com/nismod/nismod2 doi: 10.5281/zenodo.3583103

65 Usher, W., Russell, T. et al. (2019). smif v1.2.1. Available online: https://github.com/nismod/smif doi: 10.5281/zenodo.3386164

66 Smith, A., Russell, T. (2018). ukpopulation unified national and subnational population estimates and projections, including variants, *Journal of Open Source Software* 3(28), 803, doi: 10.21105/joss.00803

67 Smith, A., Russell, T., Usher, W. (2019). simim v1.1.0. Available online: https://github.com/nismod/simim doi: 10.5281/zenodo.3490526

The change to the O-D matrix is applied to the original population projection to create a custom variant. The nature of the model means that localised changes have a global impact – so the new variant projection applies to the whole country. The model is run year-on-year for all LADs in Great Britain from 2015 to 2050.

Although all the base models are constrained to the total number of migrations, applying changes to the attractiveness values will not in general conserve the total. Projected internal migrations can be scaled by a constant factor in order to scale the effects of the scenario generation to desired levels. Thus the migrations can be increased or decreased in this methodology. This methodology cannot capture changes in fertility, mortality and international migration that the economic and housing scenarios might also be expected to affect.

The resulting population scenarios are not guaranteed to 'fill' the number of dwellings provided by housing scenarios, as dwellings are only used as an attractiveness factor to create variations on internal migration. In the Unplanned and Expansion scenarios, SIMIM outputs were rescaled across the Arc region to meet the number of people-per-household observed in the (ONS-provided) baseline scenario. In the New Cities scenarios, population scenarios were generated using constant people-per-dwelling numbers for each LAD, taken from the base year (2015), and multiplied by the projected total number of dwellings in each LAD within the Arc. This guarantees population scenarios which are consistent with the housing scenarios that are a primary dimension of the analysis, while also giving some indication of the effects of relative attractiveness of LADs within the Arc and potential origins of internal migration to the region.

2 Urban Development Model (UDM)

The UDM has been developed to simulate the impact of future population growth on land-use through urban development. The output from future population simulations (supplied by SIMIM) and employment forecasts are, for each scenario and time period, used to drive an estimate of the total land required to satisfy demand. UDM simulates the possible spatial pattern of land development associated with the population prediction for each zone. The UDM comprises a cell-based hybrid spatial Multi-Criteria Evaluation (MCE) model and Cellular Automata (CA) model, with spatial MCE analysis used to obtain a ranking of the suitability of development within each simulation zone (in this case Local Authority District (LAD) areas) and relative to the entire Arc region. The CA model is then used to simulate the development of land for housing on the basis of this ranking.

UDM uses a set of spatial attractors (S) and weights (W) to characterise the influences that may drive the spatial pattern of land development. Such attractors could include information on the performance of local schools, local accessibility (distance) to shops, services or transport hubs, combined into a single metric using a Linear Weighted MCE approach. Land precluded from development is represented using a spatial field of constraints (Con), a binary raster layer which also includes current development.

UDM estimates the total area of land to be developed in each zone on the basis of:

$$L_j^d = \Delta EP_j / EP_j^p \qquad (1)$$

where for $\forall j \in N$ ΔEP_j is the magnitude of employment and population change ($EP_j - EP_j^{base}$) and EP_j^p is either the current employment + population density (EP_j^{base}/L_j^{built} where $L_j^{built} = L_j^b + L_j^u$) or the desired employment+population density per zone. Employment and population numbers are summed for each zone since it is not known if current development land is residential or non-residential. In the case where EP_j^p is set as the existing employment and population density, this ensures that future development within a zone retains the spatial characteristics of the zone (i.e. high density areas will continue to contain high density housing and employment accommodation, whilst low density areas will not experience densification in the future). A further required input to the CA part of UDM is a spatial field (grid) of the land available for development, L_j^a. This is by default set to be $\neg Con$ (i.e., all land that does not form a constraint in the derivation of S). Finally, the area of cell size, c_{area}, employed in tessellating each zone for the grid-based inputs is required.

The initialisation of the CA urban development algorithm is processed by calculating and then ranking the mean suitability score for each zone S_j^x from S. Zones are then processed on the basis of descending S_j^x. Iteration over the ranked zones is initiated by calculating S_j^{max} (the maximum suitability score of any cell in the zone j) and then calling the CA urban growth method (see Ford et al, 2019 for more detail).

3 Energy

The energy supply system is undergoing enormous change to deliver against all aspects of the 'trilemma' – cost, security of supply and decarbonisation. Therefore, robust decision making on infrastructure requires integrated models to perform analytics across the entire energy supply chain – from supply, generation, transmission, distribution and to end use.

3.1 Multi-scale modelling of integrated energy supply systems

The energy supply model in the ITRC-MISTRAL programme is based on the Combined Gas and Electricity Network model – CGEN.[68,69] The ITRC-MISTRAL energy supply model is rebuilt from the ground up and includes characterisation of the energy supply system at both transmission and distribution scales. The energy supply model performs operational analysis over multi-time periods considering electricity, natural gas, hydrogen and heat supply systems and their interactions.[70]

68 Chaudry, M., Jenkins, N. and Strbac, G. (2008). Multi-time period combined gas and electricity network optimisation. *Electric Power Systems Research*, 78(7), pp. 1265–1279. doi: 10.1016/j.epsr.2007.11.002.

69 Chaudry, M., Jenkins, N., Qadrdan, M. and Wu, J. (2014). Combined gas and electricity network expansion planning, *Applied Energy* 113, pp. 1171-1187. 10.1016/j.apenergy.2013.08.071.

70 Jayasuriya, L. et al. (2019). 'Energy hub modelling for multi-scale and multi-energy supply systems', 2019 IEEE Milan PowerTech, PowerTech 2019. IEEE, pp. 1–6. doi: 10.1109/PTC.2019.8810641.

The model minimises total operational costs to meet energy demands across the energy supply system. The operational costs of the energy system are derived from energy supply, emissions and unserved energy. The cost minimisation is subjected to constraints which are derived from the operational characteristics of assets and the supply and demand balance of the energy system.

Energy transmission components in the model are connected to the electricity and natural gas networks. These two transmission networks interact through gas fired power generators. Energy resource supplies, generation technologies and networks are explicitly modelled. Detailed modelling methods are used to represent seasonal gas storage operation, variable generation of renewables and operation of interconnectors. Energy supply at the transmission level meets demands from large industrial consumers and energy flows to the distribution networks. Figure A1 illustrates a stylised representation of the key electricity and gas transmission system components modelled.

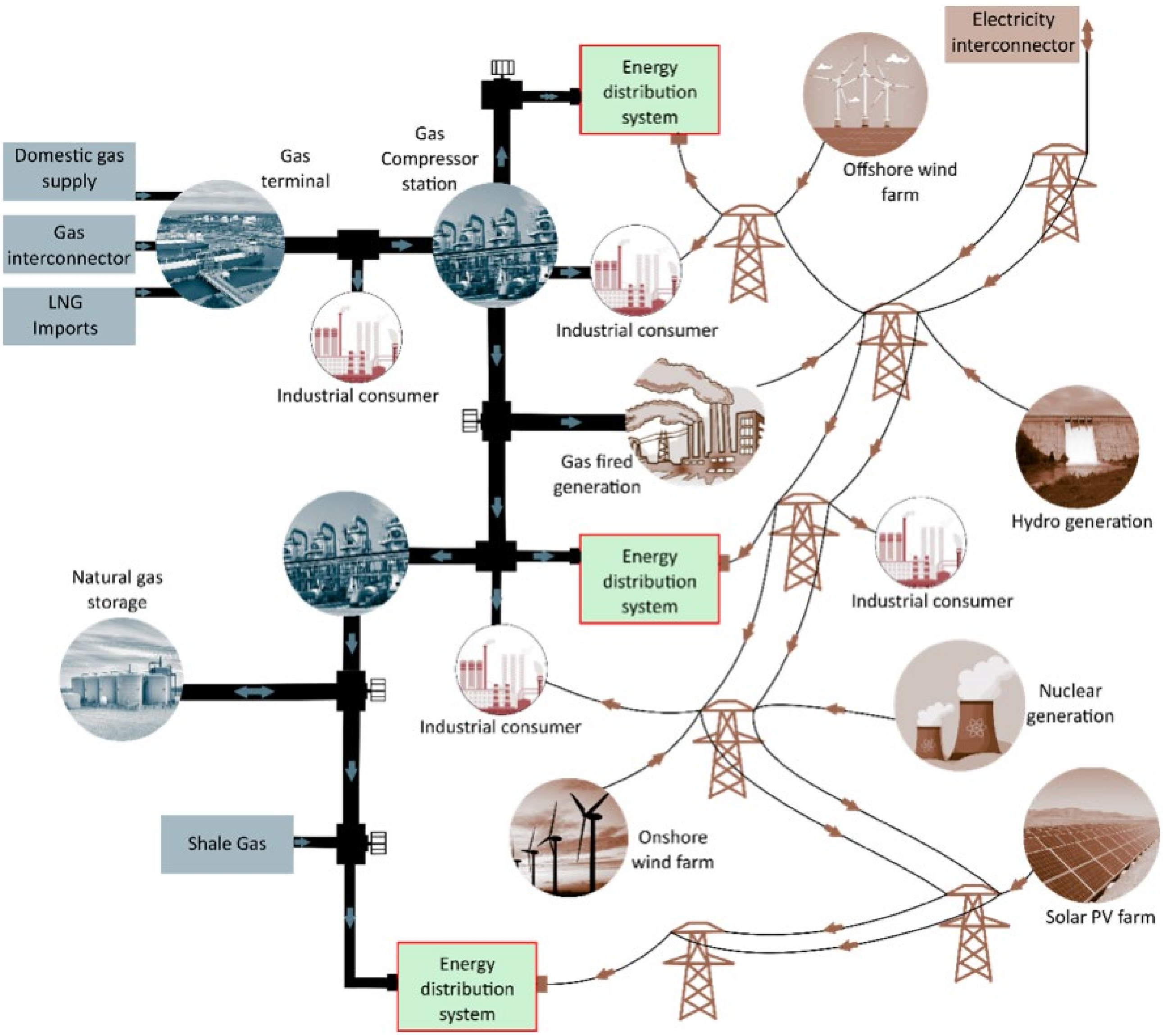


Figure A1: Stylised representation of electricity and gas transmission systems.

Within energy distribution systems, integrated electricity, natural gas, hydrogen and heat distribution systems are considered. To form the integrated framework of various energy carriers (via energy conversion technologies) an 'energy-hub' concept is adopted. The energy hub utilises available regionally distributed energy resources and transmission grid supplies to meet electricity, natural gas and heat demands of residential and commercial consumers. Constraints from each technology component and network energy flow capacities are considered in the model. A simple illustration of an energy hub is shown in Figure A2.

The modelling approach in ITRC-MISTRAL offers a rich level of disaggregated temporal and spatial representation of energy supply systems. This allows detailed analysis of future energy supply systems under various strategies such as integration of high levels of renewables, expansion of community and distributed generation, benefits of electrical storage devices, greater consumer participation and the challenge of decarbonising heat and mobility.

Key outputs from the model include the energy supply mix at both transmission and distribution, total emissions from the electricity system and cost of operation. Additionally, the model is also able to offer insights into the impacts of user defined infrastructure expansion options.

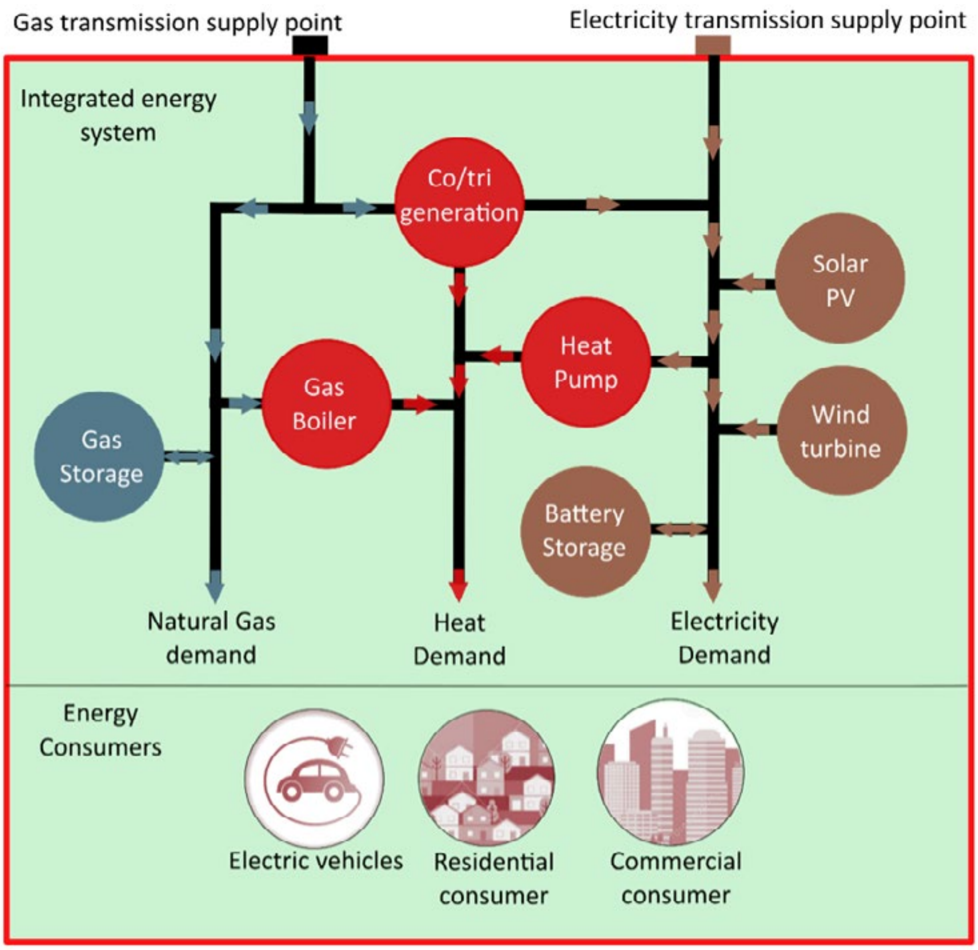


Figure A2: Energy hub representation of a distribution system.

3.2 Modelling of the Oxford-Cambridge Arc

The energy supply model is utilised to analyse the Arc scenarios alongside specific heat system strategies for the Oxford-Cambridge Arc. This region is modelled using the existing spatial granularity[71] by which the distribution regions are represented. The energy distribution regions are represented by 29 energy hubs as shown in Figure A3. Three of these energy hubs (out of 29) characterise energy systems within the Oxford-Cambridge Arc (1: Western-Oxford, 2: Central-Milton Keynes and 3: Eastern-Cambridge – see Appendix B Table B1).

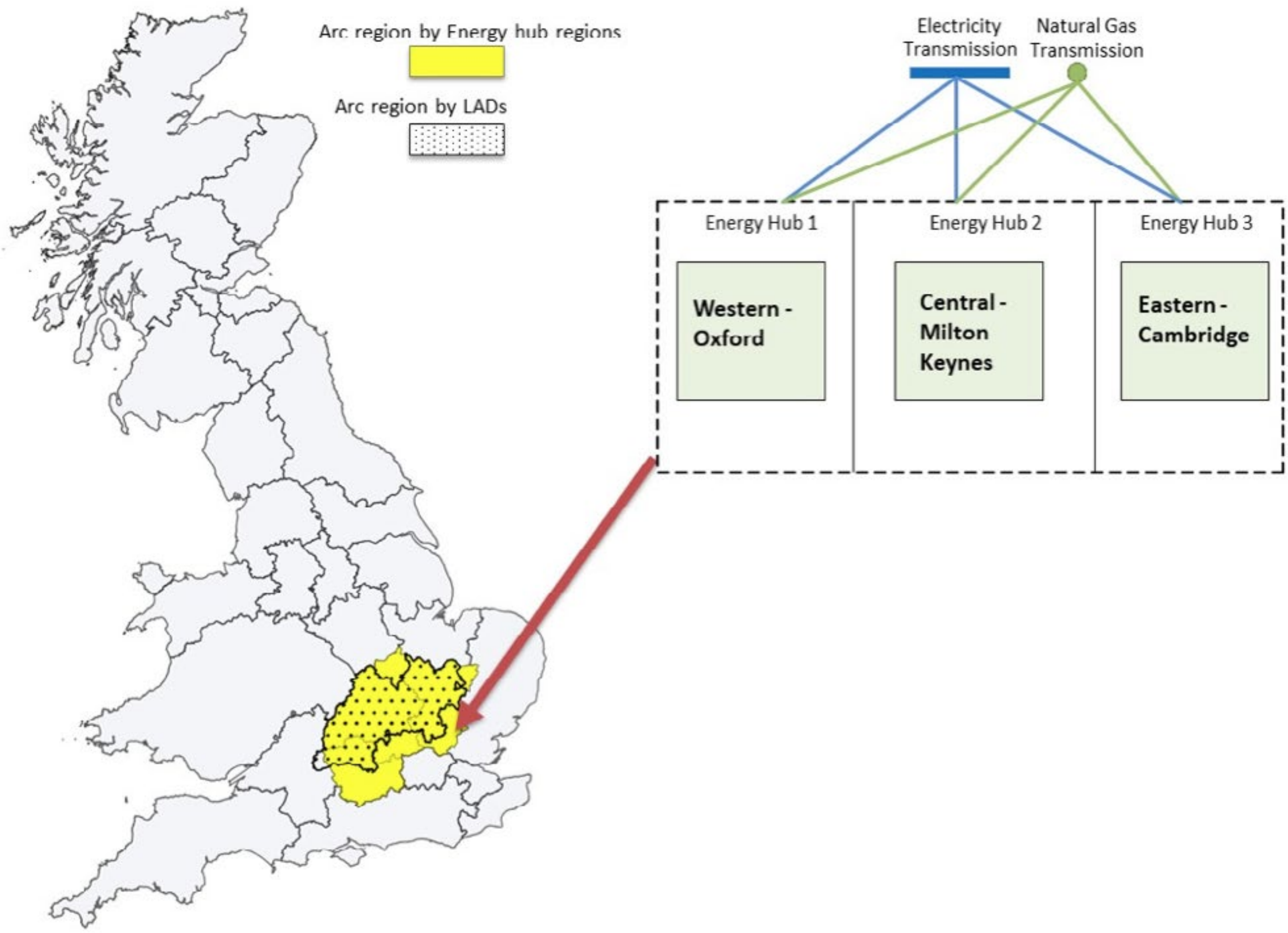


Figure A3: Representation of energy distribution systems across GB and Oxford-Cambridge Arc region.

The energy distribution regions are connected to the transmission networks. Figure A4 shows GB electricity and natural gas transmission network representation within the energy supply model.

71 The energy hub region boundaries are designed to be a collection of Local Authority Districts (LAD) such that whole GB is represented (see Appendix B).

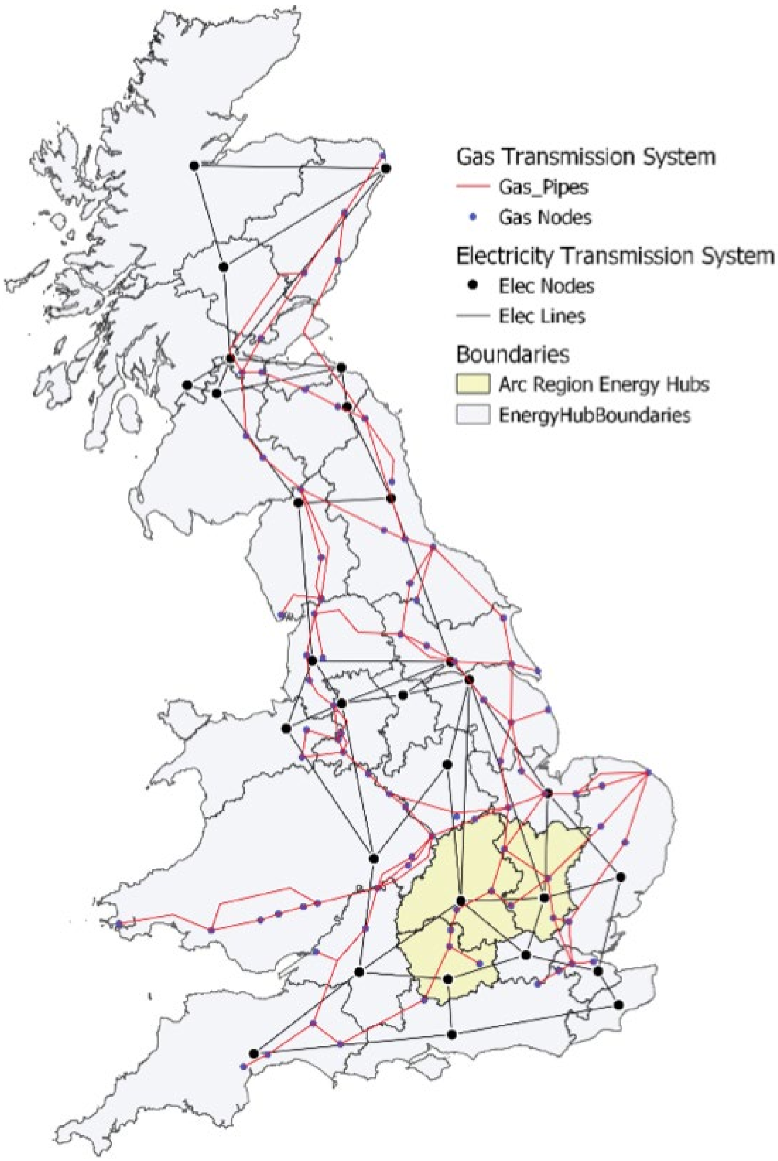


Figure A4: GB electricity and natural gas transmission network representation.

3.3 Simulation process:

3.3.1 Model setup

The GB electricity and gas transmission system and 26 energy hubs (i.e. excluding the three energy hubs that represent the Oxford-Cambridge Arc region) follow the generation and network 'capacity pattern' (out to 2050) as outlined by the 'Two Degrees' Future Energy Scenarios (FES).[72]

The three energy hubs representing the Oxford-Cambridge Arc regions are subjected to various supply side assumptions (technology, resource constraints) to year 2050 which describe various pathways to meet energy demand. Table 3 of the main report illustrates the strategies applied across the three Arc region energy hubs. The strategies were chosen so that they cover a range of possibilities across the Arc, from electrical domination to use of green gases and district heat network solutions. Some of these strategies meet more stringent emission targets than others (i.e. net zero).

The heating demand is projected by the energy demand model[73,74] for years 2015, 2030 and 2050. From the final heating demand, a maximum share is assigned to different technologies for the supply of heat. This is reflected in the maximum installed heat supply capacity for each technology within the Arc region.[75] These technology shares assigned across heating strategies for 2050 are shown in Figure A5.

72 National Grid (2019). Future Energy Scenarios. To take account of the differing demand requirements for the Arc scenarios the 'capacity pattern' from the 'FES two degrees' scenario is sized linearly so that supply matches demand whilst maintaining capacity margins (see Appendix C).

73 Eggimann, S., Hall, J. W. and Eyre, N. (2019). A high-resolution spatio-temporal energy demand simulation to explore the potential of heating demand side management with large-scale heat pump diffusion. *Applied Energy*, 236(June 2018), 997–1010.

74 Eggimann, S., Usher, W., Russell, T., Lemmen, L., Dickinson, R. (2019). 'High-Resolution Energy demand model (HIRE) v0.9.11'. Available online: https://github.com/nismod/energy_demand doi: 10.5281/zenodo.3346798

75 Distinct heat strategy options were modelled. Technology uptake within these strategy options considered key elements such as maturity, annual build rates, annual and peak heat demand and capacity margin factors.

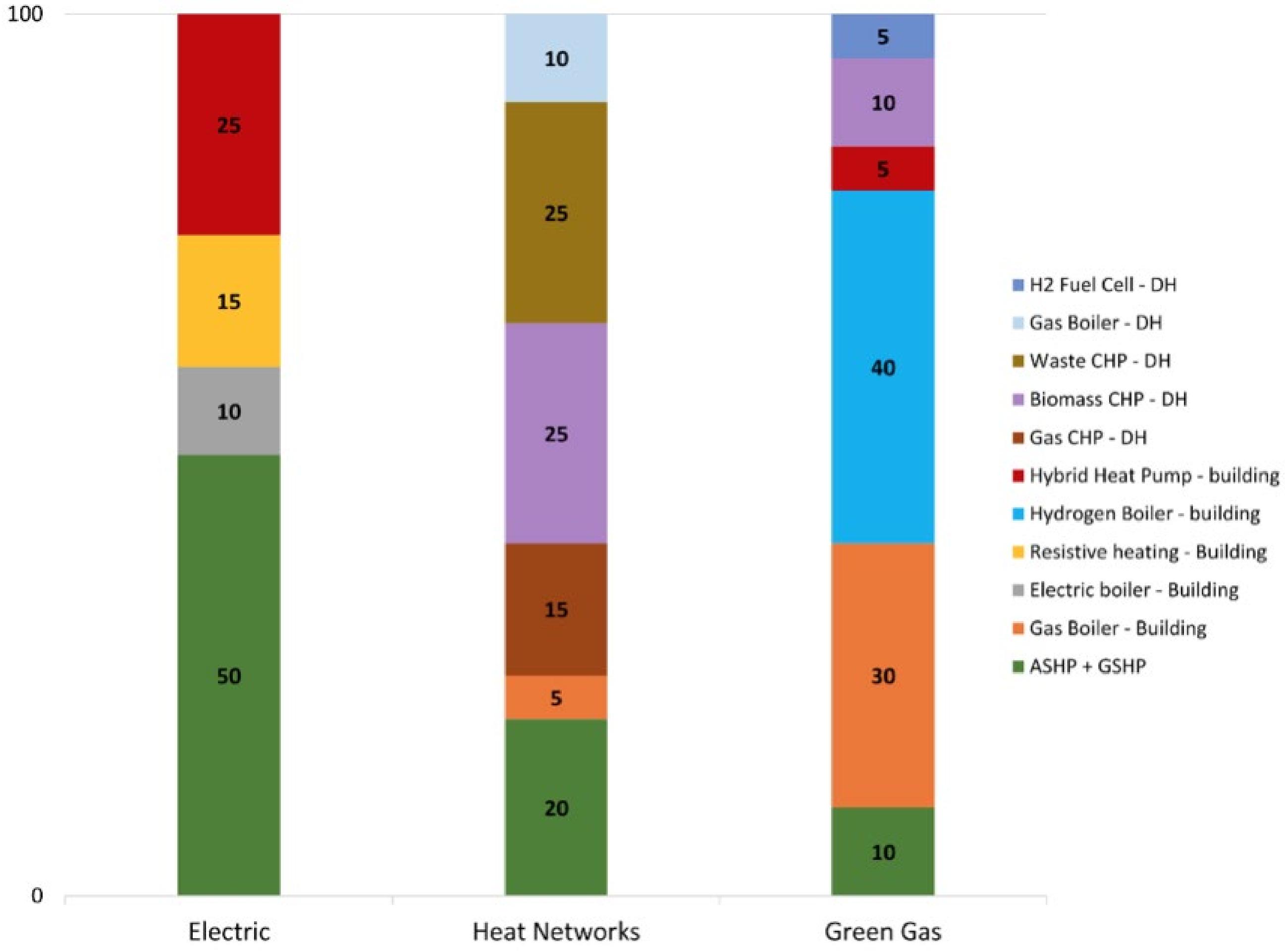


Figure A5: Maximum allowable heat supply for different heating technologies across strategies for 2050.

3.3.2 Model simulation

The Arc scenarios are analysed by applying the four heat supply strategies within the Arc region: (1) Unconstrained; (2) Electric; (3) Heat Networks; and (4) Green Gas.

Each energy supply model run performs operational analysis of the entire energy system[76] for a simulation year. Within each year, four seasons are modelled with one representative week for each season using hourly time granularity.

76 Default model run setup of the energy supply model performs analysis for the whole GB system. The outputs are recorded at regional, and at transmission network level. This report presents the outputs focusing on the Arc region only.

4 Transport

NISMOD v2 Transport Model[77] is a national-scale (Great Britain) transport model developed to support policy making regarding future infrastructure. It forecasts the impact of various endogenous and exogenous factors on transport demand and capacity utilisation, following an elasticity-based simulation methodology similar to the original ITRC model (NISMOD v1). The new model, however, is explicitly network-based, in that that the demand is assigned to the transport network to obtain more accurate predictions of travel times, travel costs and capacity utilisation.

4.1 Road transport model

The NISMOD v2 Transport Model predicts vehicle demand (inter-zonal flows) for passenger and freight vehicles, and stochastically simulates road traffic on all major UK roads including A-roads and motorways. The number of lanes on each road segment has been estimated by map-matching AADF count point locations to the OpenRoads major road network. This has allowed a distinction between single and dual carriageway A-roads, which are then assumed to have 1 and 2 lanes per direction, respectively.

It is currently the only national-scale road traffic model capable of routing-based network assignment and provisioning a national-scale origin-destination matrix (on TEMPRo & LAD spatial zoning levels), while achieving a respectable match with AADF traffic counts, total vehicle kilometres, expected number of car trips, and the observed trip length distribution from the National Travel Survey. The freight model has been modelled after the DfT's 2006 Base-Year Freight Matrices model, which includes traffic flows for freight vehicles (vans, rigid HGVs, and articulated HGVs) between local authority districts (LADs), sea ports, selected airports, and major distribution centres. The accuracy of the freight model is mostly limited by the spatial zoning system (LAD).

Demand prediction for the transport model is given by an elasticity-based model that can predict future vehicle flows from exogenous (scenario-based) changes in population and GVA, and endogenously calculated changes in inter-zonal travel time and travel cost (but also dependent on exogenous interventions such as new road development and congestion charging policies).

Congested travel times on individual road links have been modelled separately for each hour of the day, using the speed-flow curves estimated on English roads (DfT's 2005 FORGE model), the overcapacity formula from WebTAG, and the passenger car unit (PCU) concept to capture different vehicle sizes.

77 Lovric, M. et al. (2019). 'NISMOD Transport v2.2.1' Available online: https://github.com/nismod/transport doi: 10.5281/zenodo.3583128.

The network assignment exists in two versions and has been implemented using state-of-the-art routing algorithms. The routing version uses an A* heuristic search algorithm to find the fastest path between two locations using congested link travel times, while the route-choice version uses an advanced discrete-choice model (path-size logit) to choose the optimal path based on distance, travel time, travel cost (fuel and road tolls), and the number of intersections.

The route-choice version of the network assignment uses a pre-generated route set, which consists of more than 90 million different route options, enabling the national-scale assignment to run within minutes, despite each individual vehicle trip being simulated separately (including time of day choice, engine type choice, route choice).

The model can assess different scenarios of fuel efficiency and engine type market share (i.e. internal combustion engines on petrol, diesel, LPG, hydrogen or CNG; hybrid EVs on petrol or diesel; plug-in hybrid EVs on petrol or diesel; fuel cell EVs on hydrogen, and battery EV). This scenario analysis can be used to test policies such as the fossil fuel phase-out.

Electricity and fuel consumption are calculated using the four-parameter formula from WebTAG. Behavioural assumptions are made for plug-in hybrid EVs (electricity on urban, fuel on rural road links).

Interventions such as new road development, road expansion with new lanes, and congestion charging zones can be dynamically implemented in each simulated year.

The model can output various metrics at the road link level (e.g. road capacity utilisation, peak hour travel times), zonal level (e.g. vehicle kilometres, EV electricity consumption), inter-zonal level (e.g. predicted vehicle flows, average travel times, average travel costs) and national level (e.g. total CO_2 emissions, total energy consumptions). The outputs are in csv and shapefile format, allowing them to be visualised with a software of choice.

4.2 Rail model

The NISMOD v2 Transport Model also includes a national-scale rail model for predicting future station usage, using base year data for 3054 stations covering National Rail, London Underground, Docklands Light Railway, London Trams (previously Croydon Tramlink), Manchester Metrolink, and Tyne & Wear (Newcastle) Metro.

The demand model is elasticity-based, and can predict station usage (entry + exit) from exogenous inputs including: population, GVA, rail fare index, generalised journey time (GJT) index and car trip costs (which can be provided as an input or calculated from the outputs of the NISMOD road model). Demand elasticities of rail fares and GJT vary between different areas of the country (London Travelcard, South-East, PTE, other).

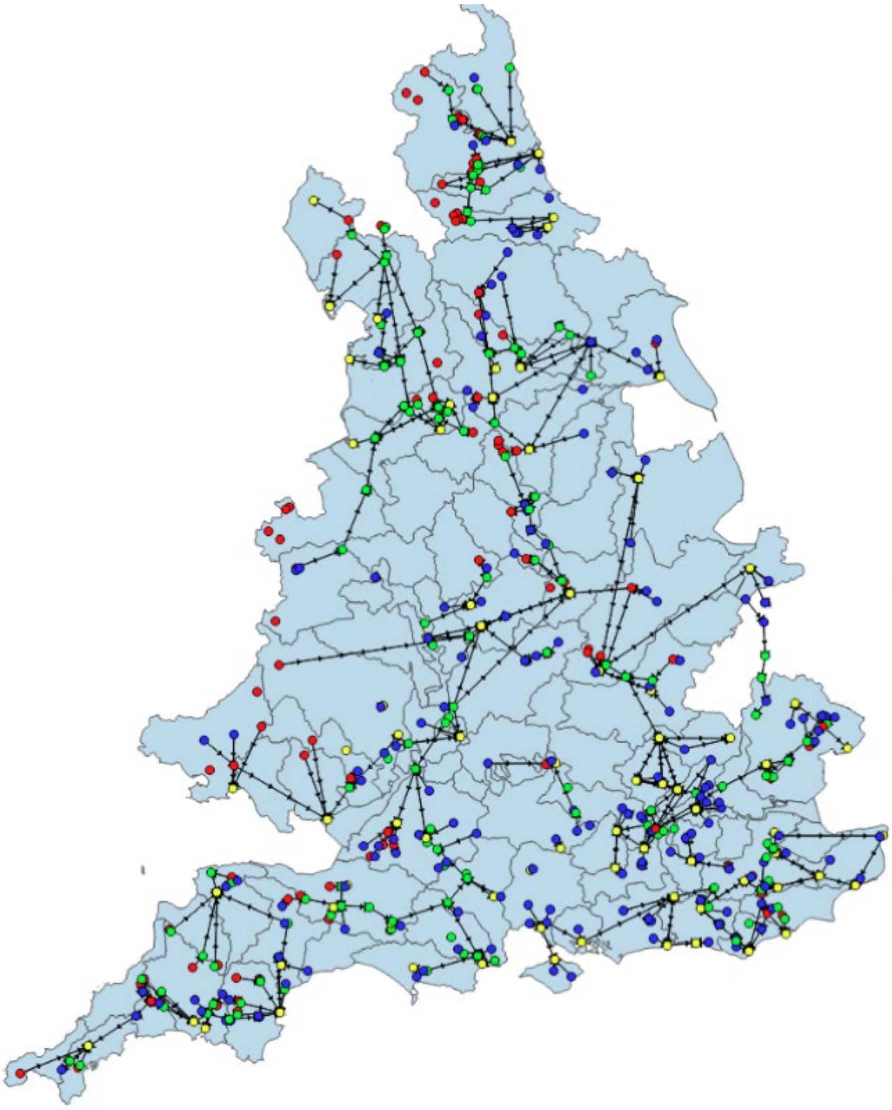
The model capabilities include an assessment of building new rail stations in future years.

5 Water

5.1 Wathnet Methodology

A water resource system model of England and Wales (WREW hereafter) has been developed for this study (Figure A6). It includes all major water supply assets (reservoirs, boreholes, transfers, water treatment works, pumped storage, desalination plants and river abstraction points) that are connected into England and Wales's wider water network via any river or transfer of significance (i.e. > 2Ml/d). This includes more than 90% of England and Wales's population and water demand, and more than 80% of their combined land area.

Figure A6: GIS depiction of the water resources model, WREW, with modelled catchment boundaries shown in blue. Rivers are not shown but do form links in the model. Blue points are sources of water, red points are reservoirs, yellow points are demand nodes, green points are water treatment works or junctions, black lines are transfers, rivers are included in the model but not shown in this figure for readability.



WREW is the product of an extensive collaboration led by the University of Oxford between a range of stakeholders: England and Wales's environmental agencies, UK-based water consultancies, the Water UK council, and all of England and Wales's water supply companies. The water system formulation in the model is based on communications with, and datasets provided by, the above stakeholders. This formulation includes: pipe capacities, treatment works capacities, reservoir capacities, abstraction and operational licence conditions, operational preferences, control curves, system connectivity, and asset locations where necessary (e.g. for river abstractions or boreholes). Beyond its use for this research, WREW will become a key tool for England's Environment Agency (EA) that can provide them with a model-based national perspective on droughts, policy reform and infrastructure planning.

WREW is simulated at a daily time-step using the WATHNET water resource simulation software.[78] Every time-step, WATHNET solves a mass balance optimization problem that allocates water between model nodes, via arcs, under both constraints inherent to mass balance (e.g. nonzero flows and storages) and constraints set out by the water system's formulation (e.g. pipe capacities and minimum required river flows). The solver minimizes a set costs associated with each model arc, performed by Network Linear Programming. These costs do not represent literal economic costs but are instead used to direct the model's behaviour according to operator preferences. For example, if one source is preferable to another its cost is set lower than the other, if one is preferable during summer and one during winter the arc costs are updated to reflect this. Arcs and nodes have their own scripts for which custom rules can be set, allowing incredibly detailed implementation of operator preferences and complex licences. To enable the solver to cope with this high level of customisation, which may introduce non-linearity or discontinuity, it is run repeatedly every time-step to enable navigation of the decision space. WATHNET is also highly efficient in its simulation; WREW contains 1252 nodes and 1756 arcs yet one year of simulation at daily timestep takes around only 2 minutes on a 3.6GHz processor. For context, the similar sized CALVIN water resource simulation model runs at around 10 minutes per year at a monthly timestep on a 2 GHz PC[79] (we note this is for context and not comparison since CALVIN's simulation philosophy is inherently different; it is a perfect foresight optimization model that represents operation as a release sequence as defined in Dobson et al. (2019).[80]

As one would expect from any national scale water resource simulation model, a range of assumptions (beyond those described in the following sections) have gone into its creation. These can be separated into modelling assumptions that have been informed by water company instruction/practice, and assumptions that are primarily the result of data/information availability or the scope of work.

78 Kuczera, G. (1992). Water supply headworks simulation using network linear programming. *Advances in Engineering Software*, 14(1), 55–60.

79 Harou, J. J., Medellín-Azuara, J., Zhu, T., Tanaka, S. K., Lund, J. R., Stine, S., … Jenkins, M. W. (2010). Economic consequences of optimized water management for a prolonged, severe drought in California. *Water Resources Research*, 46(5).

80 Dobson, B., Wagener, T., & Pianosi, F. (2019). An argument-driven classification and comparison of reservoir operation optimization methods. *Advances in Water Resources*, 128(October 2018), 74–86.

Company informed assumptions include:

- Aggregation of some reservoirs that supply a single treatment works,
- Representing redistribution of water in the unmodelled distribution network by allowing multiple sources/transfers to deliver water to the same demand node,
- The omission of small sources, particularly those with <1Ml/d – which is WATHNET's solver accuracy.

Instead, assumptions that are the result of limited data/scope are:

- Instantaneous travel time along arcs (with the exception of a few large aqueducts whose flow travel times are known),
- Reservoirs have zero evaporation (with the exception of a few large surface area reservoirs for which an evaporation relationship is well described), we note here that the UK experiences low rates of evaporation and that most reservoirs have evaporation lower than WATHNET's solver accuracy of 1Ml/d,
- Water quality is not modelled but instead assumed that it will always be acceptable provided that volumetric licence conditions and minimum required flow volumes are met,
- The decision making of water companies during a drought is highly complex due to a range of pressures that cannot be modelled, we have worked with water companies to represent these in an acceptable way but the full range of options available under drought conditions was considered outside the scope of this work.

6 Digital communications

The 5G assessment model developed here can undertake system-level evaluation of wireless networks, to help quantify the capacity, coverage and cost of different 5G deployment strategies. The capacity of a wireless network in a local area is estimated using the density of existing cellular sites, the spectrum portfolio deployed and the current technologies being used (either 4G or 5G for mass data transfer). When supply-side infrastructure changes are made, such as building new cellular sites or adding new spectrum bands, the incremental enhancement of such decisions can be quantified in terms of the improved cellular capacity and coverage, as well as in terms of the required investment.

The model used is a high-resolution spatially-explicit implementation of a telecommunication Long Run Incremental Cost (LRIC) model. The model code, cdcam,[81] is made available under an open-source license, unit-tested and thoroughly documented online.

81 Oughton, E.J., and T. Russell (2019). The Cambridge Digital Communications Assessment Model v1.0.2. Available online: https://github.com/nismod/cdcam doi: 10.5281/zenodo.3583132.

For 5G assessment, an infrastructure planning simulation model is developed which consists of a set of interconnected software modules. The model represents the key rollout period from 2020 to 2030, across spatial zones in the Arc, as illustrated in Figure A7.

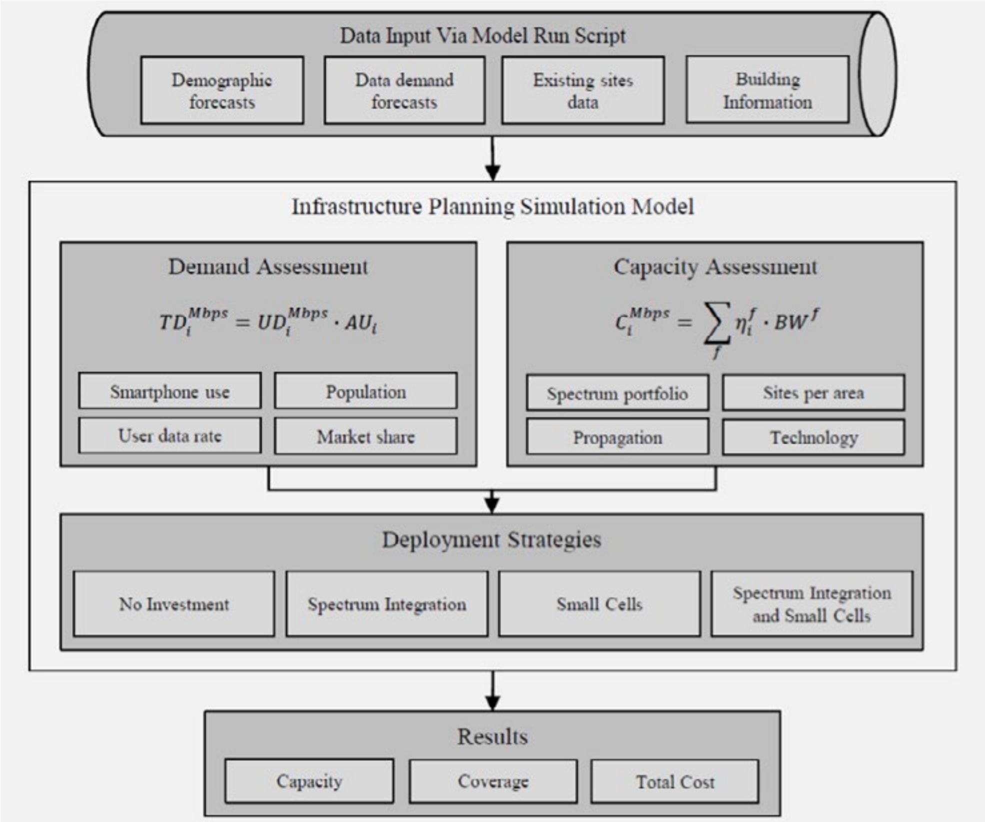


Figure A7: Digital communications system-level evaluation framework.

Necessary data inputs include spatially disaggregated demographic forecasts, taken from SIMIM in this study, as well as forecasts on how per user data demand will evolve in the future. Geospatial information is also required for site locations, as well as data on the available spectrum portfolio by carrier frequency, bandwidth and technology generation.

6.1.1 Demand assessment

The mobile demand assessment module takes into account the two main drivers of demand for cellular capacity: (i) the per user throughput rate and (ii) the number of users in an area. The total number of active users accessing the cellular network in an area is estimated and multiplied by the average user data rate to obtain the total data demand being placed on the radio access network.

Per user data demand is taken from the widely-used Cisco traffic forecast.[82] The adoption of unlimited data plans is likely to have a substantial impact on data growth, with UK mobile traffic expected to grow at 38.5% Compound Annual Growth Rate (CAGR) over the coming years.

82 Cisco (2017). VNI Mobile Forecast Highlights Tool.

Population scenarios at Local Authority District level are disaggregated to 9,000 Postcode Sectors using weights based on shares of 2011 census population. We model a hypothetical operator with a market share of 25% of users, in line with the UK's Mobile Call Termination Market Review.[83] It is reasonable to expect that not all users will access the network at once, and therefore an overbooking factor (OBF) of 50 is used, which is standard practice for network dimensioning traffic throughput.[84] Smartphone penetration in Britain is 80%, so only this proportion of the population is assumed to access high capacity wireless services such as 4G LTE or 5G.

6.1.2 Capacity assessment

The capacity assessment module is capable of quantifying cellular capacity expansion using three methods, including improving spectral efficiency via new technology generation, the provision of new spectrum bands and the deployment of new cells to densify the network.

The mean spectral efficiency is obtained using a stochastic geometry approach via the open-source python simulator for integrated modelling of 5G, pysim5G.[85] First, pysim5G estimates the Signal to Interference plus Noise Ratio in different urban and rural environment using industry-standard statistical propagation models. Next, a spectral efficiency is allocated for the level of received signal at the user, based on the ETSI coding and modulation lookup tables for 5G.[86] The estimated cellular capacity can then be obtained for an area by multiplying the spectral efficiency by the bandwidth of the carrier frequency. To ensure a specific Quality of Service, the stochastic approach allows the 10th percentile value to be extracted from the distribution of simulation results for each frequency. This means that the network will be upgraded to meet a desired user capacity at the cell edge with 90% reliability.

Physical sites data are taken from Ofcom's Sitefinder data and updated to be consistent with existing 4G coverage statistics released by Ofcom's Connected Nation report. In recent years, passive infrastructure sharing agreements have essentially created two physical networks in the UK, the first between Vodafone and O2 Telefonica ('Cornerstone') and the second between BT/EE and Hutchinson Three. We consider the Vodafone and O2 Telefonica ('Cornerstone') sites as the key supply-side input for (predominantly Macro Cell) sites. Representative site locations are obtained by taking latitude and longitude coordinates for individual cell assets, buffered by 80m, with the polygon centroid of touching buffers forming an accurate location approximation. This results in approximately 20,000 sites.

83 Ofcom (2018). 'Mobile Call Termination Market Review 2018-21: Final Statement – Annexes 1-15'.

84 Holma, Harri, and Antti Toskala, eds. (2012). LTE-Advanced: 3GPP Solution for IMT-Advanced. Chichester, UK: John Wiley & Sons, Ltd.

85 Oughton, E.J. (2019). 'Python Simulator for Integrated Modelling of 5G (Pysim5g)' Available online at https://www.github.com/edwardoughton/pysim5g

86 European Telecommunications Standards Institute (2018). 'ETSI TR 138 901 V15.0.0 (2018-07). 5G; Study on Channel Model for Frequencies from 0.5 to 100 GHz (3GPP TR 38.901 Version 15.0.0 Release 15)'.

The statistics are disaggregated by ranking the revenue potential of each postcode sector and calculating the cumulative geographic area covered using the expectation that mobile networks operators (MNOs) rationally deliver 4G coverage to the highest revenue sites first. This approach is consistent with how MNOs deploy new cellular generations.

Figure A8 illustrates the UK's existing national spectrum portfolio, broken down by carrier frequency, bandwidth and operator.

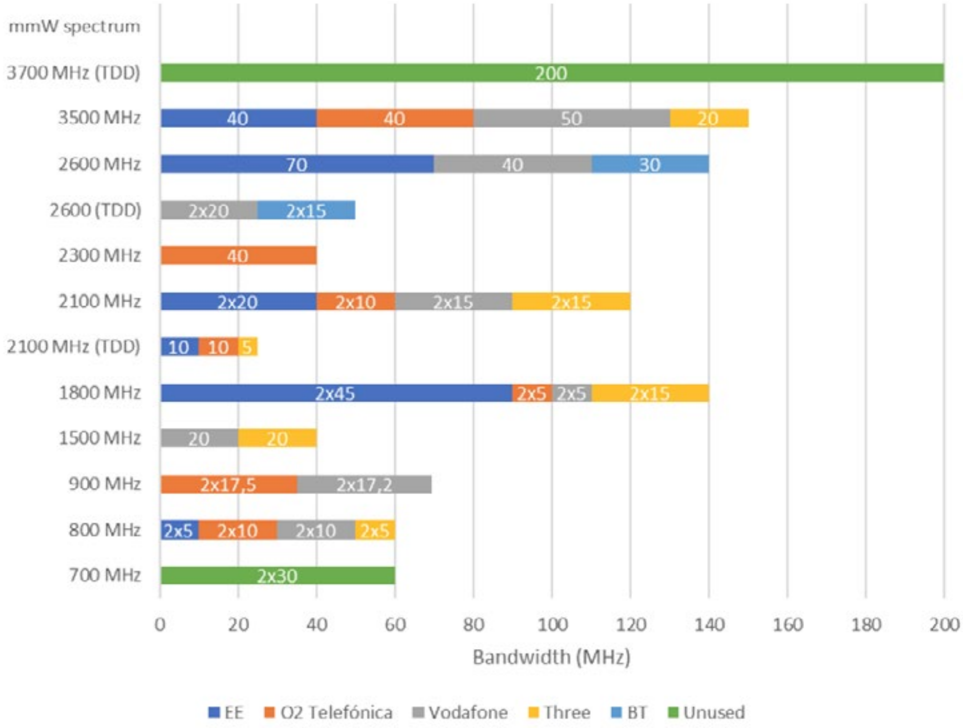


Figure A8: Spectrum portfolio by carrier frequency, bandwidth and operator.

This assessment considers a hypothetical operator, representing a set of average operator characteristics. A set of representative 4G LTE and 5G New Radio (NR) carrier frequencies and bandwidths are tested in Frequency Division Duplex mode. These frequencies consist of 10 MHz bandwidth for each of the 700 MHz, 800 MHz, 1.8 GHz and 2.6 GHz bands, 40 MHz bandwidth for 3.5 GHz, and 100 MHz bandwidth for 26 GHz.

The Total Cost of Ownership is estimated for each asset by calculating the Net Present Value of the initial capital expenditure required in the first year of deployment as a one-off cost, combined with the ongoing operating expenditure over the lifetime of the asset (with opex being 10% of the initial capex value for all active components, annually). A discount rate of 3.5% is used over a period of 10 years. This calculation does not consider price trend changes and assumes a 10-year lifespan of Macro Cells. The total cost per square kilometre for different network configurations can then be calculated based on the density of assets by area. The costs per asset item are based on the Mobile Call Termination model.[87]

87 Ofcom (2018). Mobile Call Termination Market Review 2018-21.

6.1.3 Fibre-to-the-Premises

The fixed broadband modelling assesses the cost of Fibre-to-the-Premises based on density of premises in Output Areas under different urban development scenarios.

Openreach do not make detailed fixed broadband network data publicly available to use for modelling. Therefore, the approach taken here is to use network cost information from the report produced by Tactis & Prism for the National Infrastructure Commission, as the analysts had access to the necessary Openreach network data.

With this information, a cost modelling 'geotype' approach is used which is based on the Office for National Statistics' (ONS) urban-rural local authority categories. A geotype is a group of geographical areas which have similar cost properties. The six geotypes are based on a categorisation which ranges from the densest urban conurbation, to remote rural areas.

To provide a geographically granular analysis, and to take the Arc scenarios into account, premises estimates for 2050 are taken from the Urban Development Model (UDM) outputs, where each hectare grid cell is either undeveloped or developed at a given density. These results are then aggregated to the 11,085 ONS Output Areas within the Arc. Density of premises defines the geotype, and therefore the cost per premises, for each Output Area under each urban development scenario. The total cost estimates follow from number of premises and cost per premises in each area.

7 Urban drainage

As a proof of concept, a single urban area was chosen from the 'New Settlements' scenario for the Arc region and the Urban Development Model (UDM) was used to generate a detailed land-use raster grid of cells (1 hectare in size) for that site.

The UDM uses proximity to the road network and to public transport to assign a suitability score for each cell, and used to spread development across and within plots using a Cellular Automata (CA) process. This produces detailed spatial mapping of possible land development patterns with associated average residential density at the census ward scale, which is then represented by a set of one-hectare tiles,[88] as shown in Figure A9.

This work makes use of 16 of these tiles types, 4 in each housing category of Detached (D), Semi-detached (S), Terraced (T) and Flats (F) with specified density of dwellings and proportion of impervious and green areas. These 16 tile types were then mapped to the UDM output and draped over the topography of the site using a 2m DEM as shown in Figure A10.

88 Based on work by Hargreaves, A.J. (2015). Representing the dwelling stock as 3D generic tiles estimated from average residential density. Computers, environment and urban systems 54 280-300.

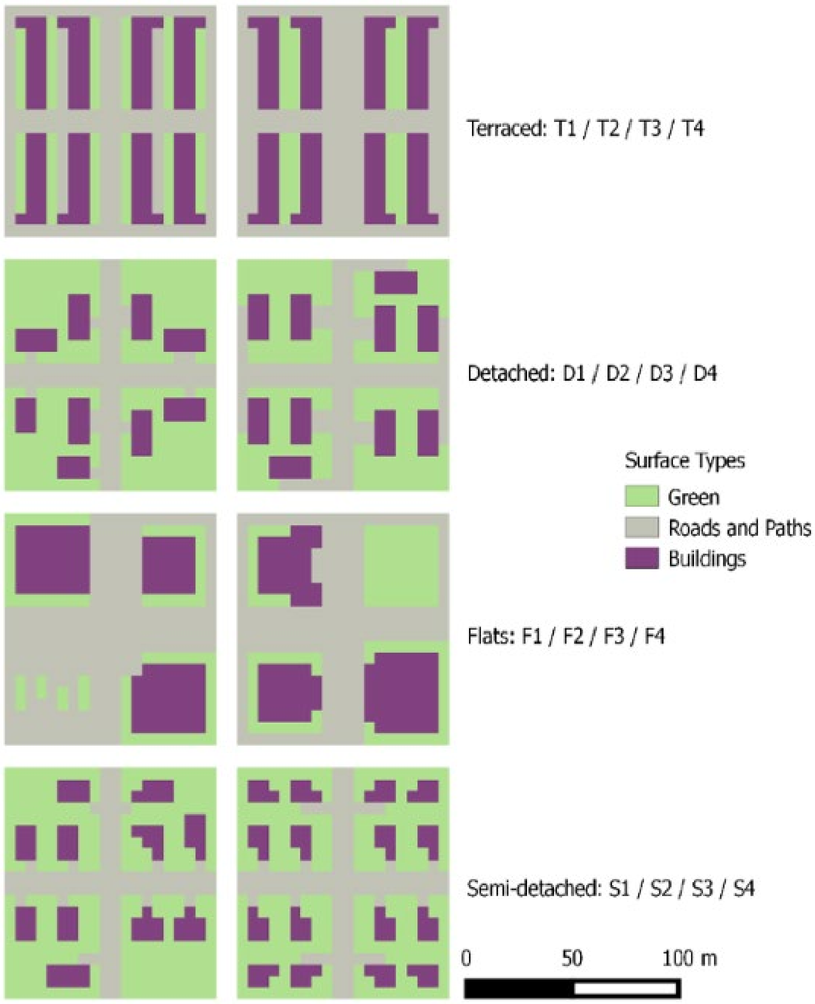


Figure A9: Example of 1 hectare tiles.

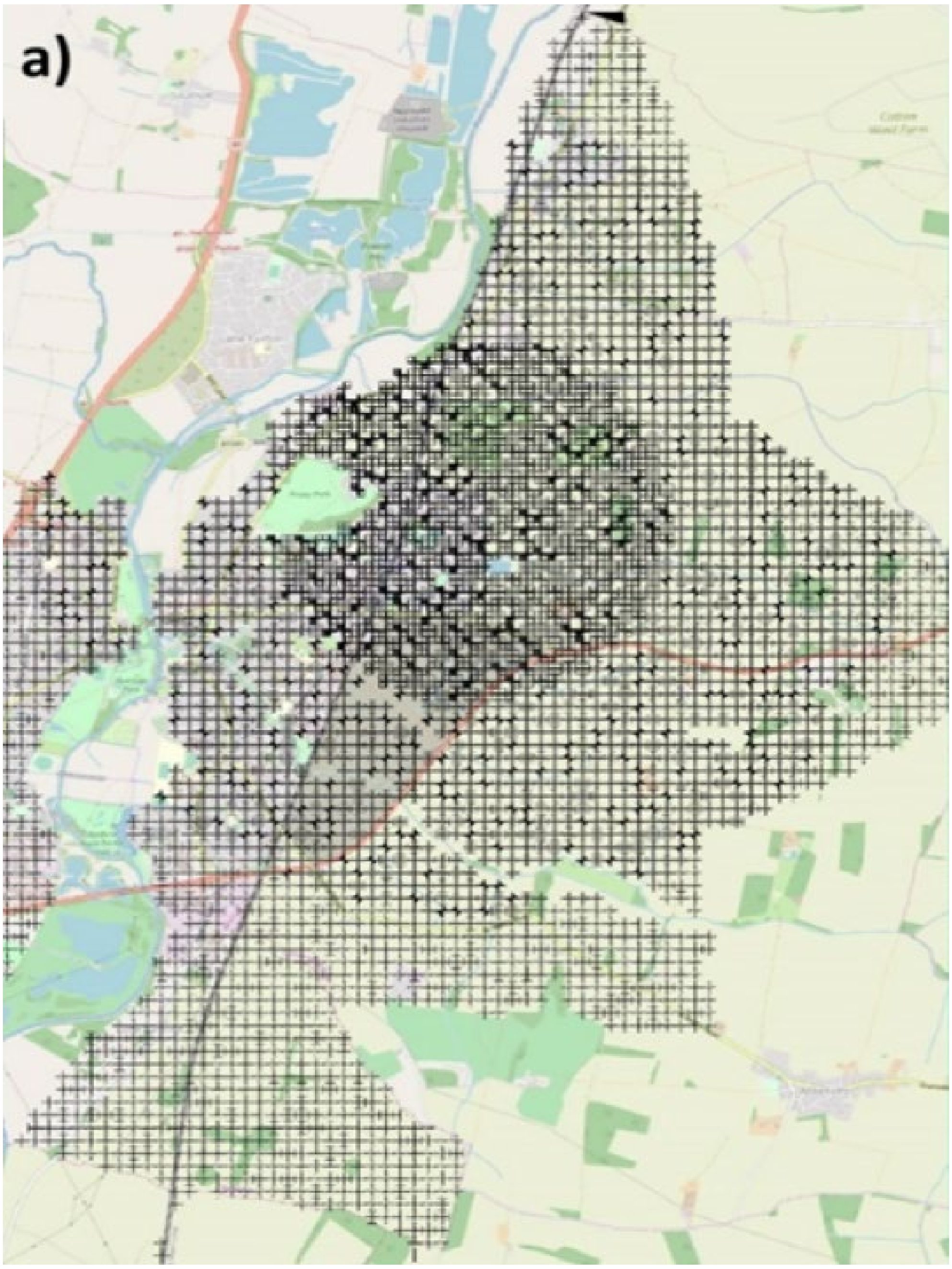


Figure A10: Location of the town showing tiles.

This model is then implemented in the CityCAT flow modelling system with buildings, green and impermeable spaces all represented. A design storm is applied to the model resulting in flooded areas which can be mapped and flood risk estimated. Various models were specified in this pilot, representing ground surface with 'burned' in by 30cm to allow flow concentration, and then with the sewer network represented by inlet gully drains at variable spacing along all roads.

8 Natural capital and green infrastructure

Natural Capital is the elements of nature that directly or indirectly produce value to people, including ecosystems, species, freshwater, land, minerals, the air and oceans, as well as natural processes and functions. Natural capital is a broad term that includes many different components of the living and non-living natural environment, as well as the processes and functions that link these components and sustain life.[89]

Green infrastructure is defined as "A network of multi-functional green space, urban and rural, which is capable of delivering a wide range of environmental and quality of life benefits for local communities."[90] This includes a very wide range of features: parks, gardens, allotments, playing fields, grass verges, landscaping, sustainable drainage features, green roofs and walls, paths, nature reserves, hedges, street trees, woodlands, wetlands, watercourses, etc. Water features are sometimes referred to separately as 'blue infrastructure', though often 'green infrastructure' is used as a catch-all term for both green and blue features. Green and blue infrastructure are a key part of our natural capital assets.

Healthy stocks of natural capital underpin the delivery of essential services for human health and wellbeing (Figure A11). These 'ecosystem services' include provision of food, fresh water, clean air, natural flood management, carbon storage, crop pollination, green space for recreation, and opportunities for interacting with and learning from nature (Table A1).

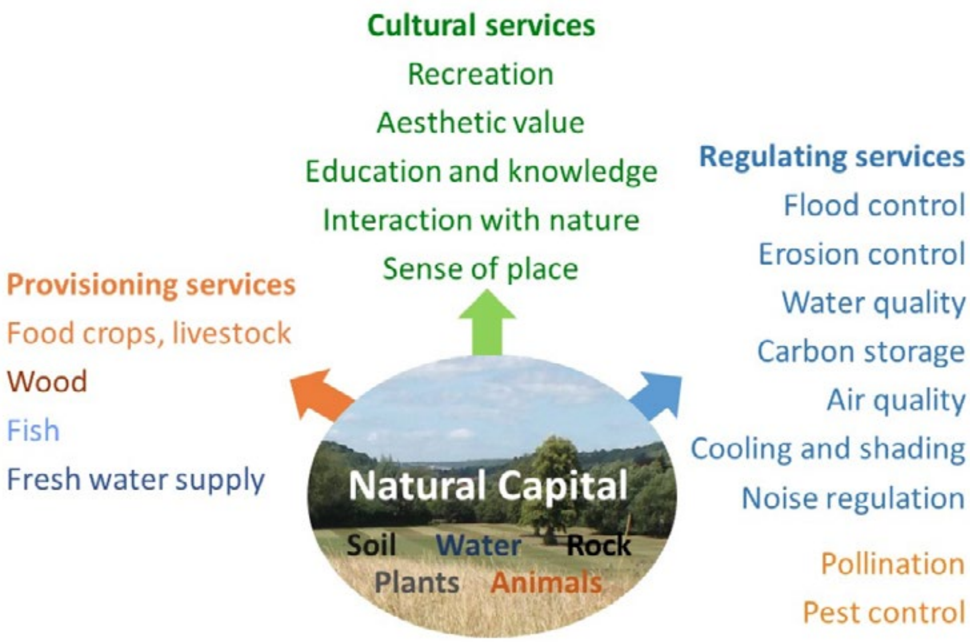


Figure A11: Natural capital stocks deliver flows of ecosystem services that underpin human health and wellbeing.

89 Natural Capital Committee (2013). The State of Natural Capital: Towards a framework for measurement and valuation.

90 MHCLG (2019). National Planning Policy Framework.

Table A1: Definitions of each of the 18 ecosystem services		
Provisioning	Food production	Arable crops, horticulture, livestock, orchards, allotments, urban food, wild food (e.g. gathering berries or mushrooms).
	Wood production	Timber, wood production for paper, woody biofuel crops, coppice wood or wood waste used for biofuel.
	Fish production	Aquaculture, commercial fishing, recreational fishing (recreational fishing is also a cultural service, but the habitat conditions match those for fish production).
	Water supply	Impact of soil and vegetation on rainwater runoff and infiltration, and thus on groundwater recharge or surface water flow.
Regulating	Flood protection	Reduction of surface runoff, peak flow, flood extent and flood depth through canopy interception, evapotranspiration, soil infiltration and physical slowing of water flow.
	Erosion protection	The ability of vegetation to stabilise soil against erosion and mass wastage by protecting the soil from the erosive power of rainfall and overland flow, trapping sediment, and binding soil particles together with roots.
	Water quality regulation	Direct uptake of pollutants by terrestrial or aquatic vegetation; interception of overland flow and trapping / filtration of pollutants and sediment by vegetation before it reaches watercourses; breakdown of pollutants into harmless forms e.g. by denitrifying bacteria that convert nitrates into nitrogen gas. Also infiltration into the ground, allowing pollutants to be filtered out by the soil and preventing pollution of watercourses – though pollutants could enter groundwater supplies.
	Carbon storage	Carbon stored in vegetation and soil. In the context of land use change (with complete loss of habitats and often major soil disturbance), this is more relevant than carbon sequestered annually. The 'time to reach target condition' reflects the time taken for a new habitat to reach a typical carbon sequestration rate for a mature habitat.
	Air quality regulation	Removal of air pollutants by deposition, absorption and/or breakdown by vegetation. Fine particles (PM2.5) are the most damaging type of pollution, but vegetation can also remove ozone and nitrogen oxides (by absorption into pores).
	Cooling and shading	Shade, shelter and cooling effect of vegetation and water, especially urban trees close to buildings, green roofs and green walls, which can reduce heating and cooling costs, or trees in urban parks which can provide shade on hot days.
	Noise reduction	Attenuation of noise by vegetation.
	Pollination	Pollination of crops (and wild plants, supporting other ES) by wild insects (mainly bees and hoverflies). Excludes pollination by managed honeybees.
	Pest control	Predation of crop or tree pests by invertebrates (e.g. beetles, spiders, wasps), birds and bats.

Cultural	Recreation and leisure	Provision of green and blue spaces that can be used for any leisure activity, e.g. walking, cycling, running, picnicking, camping, boating, playing or just relaxing.
	Aesthetic value	Provision of attractive views, beautiful surroundings, and pleasing, calming or inspiring sights, sounds and smells of nature.
	Education and knowledge	Opportunities for formal education (e.g. school trips), scientific research, local knowledge and informal learning (e.g. from information boards or experiences).
	Interaction with nature	Provision of opportunities for formal or informal nature-related activities, e.g. bird watching, botany, random encounters with wildlife, or feeling 'connected to nature'. There is some overlap with biodiversity, but access by people can have negative impacts on some wildlife habitats. Excludes recreational fishing; hunting / shooting (not covered); the intrinsic value of nature (covered by the biodiversity metric); existence value (from just knowing that nature exists).
	Sense of place	The aspects of a place that make it special and distinctive – this could include locally characteristic species, habitats, landscapes or features; places related to historic and cultural events, or places important to people for spiritual or emotional reasons.

We assess natural capital using a matrix of scores from 0 to 10 that reflect the ability of different habitat types to deliver 18 different ecosystem services. The matrix of scores has been developed over several years, drawing on a literature review of 780 papers;[91] a comparison exercise with similar scoring systems and other evidence sources and a series of expert review consultations as part of the development of an 'eco-metric' tool for Natural England for assessing the net gains or losses in natural capital that are associated with biodiversity net gain. A technical report details the rationale for all the scores, and this will be published by Natural England in due course (the draft report is available on request).[92]

For carbon storage and air quality regulation, the scores are directly proportional to biophysical evidence (carbon stored in soils and vegetation, and estimates of the health benefits of air pollution removal by vegetation in the UK Natural Capital Accounts). However the other scores are indicative rankings of different habitats. Scores for the cultural services are quite subjective, as they are highly dependent on personal views. Although some of the scores need further refinement, they are based on the best available evidence for this type of scoring system. Note that scores for the different services (e.g. carbon storage and recreation) cannot be added together because they are not in common units.

91 Smith, A.C., P.A. Harrison, M. Pérez Soba, F. Archaux, M. Blicharska et al. (2017). How natural capital delivers ecosystem services: a typology derived from a systematic review. Ecosystem Services 26: 111–126.

92 Smith, A.C., Baker, J., Berry, P.M., Butterworth, T., Dunford, R., Hölzinger, O., Howard, B., Norton, L.R., Sadler, J. and Scott, A. (2019). An Eco-metric Approach to Growing Natural Capital, Final report of Phases 1 and 2. Report to Natural England. See https://ecosystemsknowledge.net/ecometric for more information on the eco-metric approach.

The scoring matrix is shown in Appendix E. Woodland habitats tend to have high scores for the regulating and cultural services, because trees are highly effective for storing carbon, intercepting rainwater and stabilising soil as well as being attractive locations for recreation. Semi-natural grasslands also score highly for cultural services but less for services such as carbon storage and flood protection. Farmland has a maximum score of 10 for food production but tends to have low scores for most of the other services (with the exception of water provision via groundwater recharge). However certain elements of farmed landscapes (hedges, field margins, woodlands, paths) do have higher scores for regulating and/or cultural services. The matrix also includes scores for watercourses, wetlands and urban green infrastructure.

Multipliers can be applied to adjust these generic scores to reflect factors such as habitat condition, location or whether there is public access. The multipliers are based on those developed for Natural England's eco-metric tool. The eco-metric tool includes 46 multipliers, but it is not possible to apply all of these at the scale of a whole county, partly because the data is not available (e.g. on tree size), and partly because it would make the analysis too complex. We have therefore selected a few key multipliers that can be applied at regional scale:

- For food provision, we have applied a multiplier that takes account of the agricultural land class (i.e. the quality of the farmland);
- For recreation, we apply a multiplier based on the degree of public access (open access, restricted access or no access);
- For aesthetic value, we apply a multiplier of 1.1 if the area is within an AONB;
- For education, interaction with nature and 'sense of place', we apply a multiplier if the area is designated for nature or for cultural value, based on how many designations apply.

The scoring system is still being reviewed and refined, but it provides a useful way of producing maps and conducting initial scoping assessments of the impacts of land use change on natural capital. This method has been recently used to produce natural capital maps of Oxfordshire.[23] Under MISTRAL, the approach has been extended to cover the entire Arc. The base map of habitats and land use was compiled from multiple sources:

1. **Ordnance Survey MasterMap** – a very detailed and accurate map that shows individual features such as buildings, gardens, roads, roadside verges and water.
2. **Oxfordshire Phase 1 habitat and land use survey** provided under license by the Thames Valley Environmental Records Centre (TVERC). This does not include urban areas (except for relatively large green areas such as urban parks), but it provides more detailed ecological information on semi-natural grassland (acid, neutral or calcareous) and woodland (plantation or semi-natural) and also classifies agricultural land as either arable or improved grassland
3. **CEH Land Cover Map 2015**[93] – used for the non-Oxfordshire areas to distinguish arable land from improved grassland (i.e. intensive pasture).

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93 Rowland, C.S.; Morton, R.D.; Carrasco, L.; McShane, G.; O'Neil, A.W.; Wood, C.M. (2017). Land Cover Map 2015 (vector, GB). NERC Environmental Information Data Centre.

4. **Natural England Priority Habitat Inventory** – used to identify semi-natural habitats outside Oxfordshire. Although some of the other local authority districts in the Arc region also have Phase 1 habitat maps, these are not freely available.

5. **OS Greenspace and OS Open Greenspace** – green spaces such as allotments, churchyards and cemeteries, golf courses and playgrounds.

6. **Public access data** – **CROW** (open access land), **PROW** (Public rights of way, Oxfordshire only), **OrVal paths and parks** (derived for the OrVal model by the University of Exeter[94] from Open Street Map and other sources) – used as a multiplier for the service of recreation.

7. **Designated sites** – used to derive multipliers for the cultural ecosystem services:

    - AONBs
    - National Nature Reserves and Local Nature Reserves
    - Road verge nature reserves
    - SSSIs
    - Special Areas of Conservation (SACs) (protected under the EC Habitats Directive)
    - Special Protection Areas (SPAs) (protected under the EC Birds Directive)
    - RAMSAR sites (internationally important wetlands)
    - Important Bird Areas (IBAs)
    - Oxfordshire only: Local Geological Sites, Local Wildlife Sites, Proposed Local Wildlife Sites and Road Verge Nature Reserves
    - Ancient Woodland
    - Country Parks
    - Millennium Greens and Doorstep Greens
    - Green belt land

8. **Agricultural Land Classification** – indicating the productivity and versatility of farmland – used to derive a multiplier for the service of food production. This classifies land into grades 1 (best) to 5 (worst) for the whole of England. Grade 1 land is highly productive and also versatile, so that many types of crop can be grown. Grade 5 land is typically bog or moorland suitable only for extensive grazing. The 'average' grade is 3b.

These layers were combined together using a customised set of instructions written as Python code. The aim was to retain the accurately mapped OS MasterMap boundaries, but split these to create new shapes where the other datasets followed genuinely different boundaries (rather than simply differing due to less accurate mapping). We then developed a set of rules for classifying the habitat type in each land parcel, combining elements from all the different habitat information. In Oxfordshire, we also included ancient trees (from the Woodland Trust ancient tree hunt) and hedges (from Ordnance Survey), but we did not have data for street trees.

The natural capital maps were generated by applying the matrix of scores to the base maps of different habitats, and adjusting the scores by multipliers to reflect the number of habitat designations, the degree of public access, and the agricultural land class.

94 Day, B. H., and G. Smith (2018). Outdoor Recreation Valuation (ORVal) User Guide: Version 2.0, Land, Environment, Economics and Policy (LEEP) Institute, Business School, University of Exeter.

After applying the multipliers, scores were normalised back to a scale of 0 to 10 so that the highest scoring habitat with the highest possible multipliers always scores 10 out of 10.

The maps reflect the ability of the land to supply ecosystem services. They do not account for the demand for those services from people, such as how many people live close to a green space that can be used for recreation.

The maps show the scores for each of the 18 services on a scale of 1 to 10, split into broad bands, with the higher scoring areas shown in darker shades of green. For clarity, areas with very low scores (less than 1 out of 10) are omitted (i.e. white).

We also show maps of the maximum score out of all 18 services for each land parcel – in other words, the land parcels that have a high score for at least one of the 18 services are shown in a darker shade of green. On these maps, following feedback from stakeholders, we show land that scores highly for food production in orange to distinguish it from land that scores highly for multiple cultural and regulating services.

We have compiled data on potential habitat networks, including the preliminary Nature Recovery Networks being developed by local groups in line with the UK Government 25 Year Environment Plan24. These networks can be used to inform the development of a 'Green Arc' scenario, which is still in progress. For scenario analysis, the scores for each ecosystem service can be multiplied by habitat area to assess the impacts of habitats lost or gained due to land use change.

Appendix B: Energy hubs

Table B1: Modelling of the Oxford-Cambridge Arc region by energy hubs		
Energy Hub	LAD Code	LAD Name
Eastern (21) – Cambridge	E06000031	Peterborough
	E07000010	Fenland
	E07000008	Cambridge
	E07000009	East Cambridgeshire
	E07000011	Huntingdonshire
	E07000012	South Cambridgeshire
Central (22) – Milton Keynes	E06000032	Luton
	E06000042	Milton Keynes
	E06000055	Bedford
	E06000056	Central Bedfordshire
	E07000004	Aylesbury Vale
	E07000005	Chiltern
	E07000007	Wycombe
	E07000150	Corby
	E07000151	Daventry
	E07000152	East Northamptonshire
	E07000153	Kettering
	E07000154	Northampton
	E07000155	South Northamptonshire
	E07000156	Wellingborough
	E07000177	Cherwell
	E07000181	West Oxfordshire
Western (24) – Oxford	E07000006	South Bucks
	E07000178	Oxford
	E07000179	South Oxfordshire
	E07000180	Vale of White Horse

Appendix C: Energy generation capacity assumptions

Table C1: Installed power generation capacities for the national electricity transmission system and electricity distribution regions (except the Arc region).			
Generation Type	Generation Capacity – GW		
	2015	2030	2050
Transmission			
Oil	0.8	0.4	0.1
Gas CCS	0.0	6.1	11.6
Coal	13.8	0.0	0.0
Gas (CCGT + OCGT)	28.9	15.7	5.2
Hydro	1.2	1.3	1.3
Pumped hydro	2.8	4.7	5.9
Interconnectors	4.2	15.2	21.2
Other (tidal and marine)	0.0	3.1	5.8
Nuclear	9.0	11.8	15.8
Onshore wind	5.4	11.6	15.2
Offshore wind	4.3	34.0	54.2
Solar	0.5	0.7	0.9
Battery	2.7	2.7	2.7
Total	**73.5**	**107.2**	**139.7**
Distribution – Excl. Arc			
Gas (non CHP)	1.3	3.1	4.1
Onshore wind	4.0	7.4	9.9
Offshore wind	0.5	0.7	0.8
PV	12.3	28.4	40.9
CHP gas	4.9	4.4	4.1
Oil (diesel etc.)	0.6	0.2	0.0
Biomass other	2.6	2.8	2.4
Biomass CHP	0.1	1.2	1.9
Waste other	0.8	1.0	1.0
Waste CHP	0.5	0.7	0.9
Fuel cells	0.0	0.002	0.003
Vehicle to grid	0.0	4.2	8.0
Storage (battery)	0.001	6.0	10.7
Other	0.012	1.0	1.7
Total	27.5	61.3	86.1
Total capacity	**101.1**	**168.5**	**225.8**

Table C2: Installed power generation capacities for the Arc region in the Baseline scenario					
Generation Type	2015	Generation Capacity (MWe) – 2050 Baseline			
		Electric	Heat Network	Green Gas	Unconstrained
Gas (non CHP)	131	366	366	366	366
Onshore wind	141	333	333	333	333
Offshore wind	0	15	15	15	15
PV	2547	8644	8644	8644	8644
Gas CHP	465	391	388	391	391
Oil (diesel etc.)	0	0	0	0	0
Biomass CHP	7	267	739	267	267
Waste CHP	68	130	739	296	130
Fuel cells	0	0	0	148	0
Vehicle to grid	0	2453	2204	1760	2547
Transmission supply capacity	3333	6176	3542	3333	4270
Total (GW)	7	19	17	16	17

Table C3: Installed heat supply capacities for the Arc region in the Baseline scenario				
Technology	Heat Supply Capacity (MWth) – 2050 Baseline			
	2015	Electric	Heat Networks	Green Gas
ASHP + GSHP	25	1725	690	345
Gas boiler – Building	4018		173	1035
Electric boiler – Building		388		
Resistive heating – Building	502	518		
Hydrogen boiler – building				1553
Hybrid heat pump – building		970		194
Oil boiler – Building	594			
Gas CHP – DH	3		582	
Biomass CHP – DH	6		1109	444
Waste CHP – DH			1109	
Gas boiler – DH	3		388	
Heat pump -DH				
H2 fuel cell – DH				222

Appendix D: UDM results

Table D1: Total amount of land available for development in each LAD as a result of planning constraints for each scenario (ha)

LAD Code	LAD Name	Baseline	Unplanned	New Settlements	Expansion
E06000031	Peterborough	12906	25293	12920	12906
E06000032	Luton	413	757	413	514
E06000042	Milton Keynes	19063	22820	19433	19098
E06000055	Bedford	36736	41193	37039	36736
E06000056	Central Bedfordshire	30748	60029	31184	52226
E07000004	Aylesbury Vale	69884	77858	71067	73340
E07000005	Chiltern	352	95	352	13307
E07000006	South Bucks	242	71	242	6638
E07000007	Wycombe	9217	9988	9217	20163
E07000008	Cambridge	451	640	451	1038
E07000009	East Cambridgeshire	30495	56216	30501	30500
E07000010	Fenland	8516	47242	8516	8516
E07000011	Huntingdonshire	58669	76944	59126	58669
E07000012	South Cambridgeshire	51466	58895	52036	70009
E07000150	Corby	4488	5076	4488	4488
E07000151	Daventry	56918	59148	56918	56918
E07000152	East Northamptonshire	39981	42349	39984	39981
E07000153	Kettering	18536	19205	18536	18536
E07000154	Northampton	1503	2366	1503	1503
E07000155	South Northamptonshire	53119	55496	53131	53119
E07000156	Wellingborough	11877	12891	11877	11877
E07000177	Cherwell	39806	50811	40568	44725
E07000178	Oxford	342	720	342	541
E07000179	South Oxfordshire	37763	40521	37797	48511
E07000180	Vale of White Horse	39093	42035	39093	44186
E07000181	West Oxfordshire	53153	57876	53163	54183

The following table shows the total future population projected in each LAD in 2050 for each of the four scenarios to be simulated in UDM. It is not always possible to accommodate this population at current density levels due to constraints on land availability; These 'overflows' for each scenario are reported in the Results section.

Table D2: Total future population per LAD in 2050 by scenario

LAD Code	LAD Name	Current Population	Baseline	Unplanned	New Settlements	Expansion
E06000031	Peterborough	196860	232592	238906	262242	279630
E06000032	Luton	216021	254973	259864	265187	295252
E06000042	Milton Keynes	266441	323214	362597	374296	497434
E06000055	Bedford	168899	212578	237329	247396	301495
E06000056	Central Bedfordshire	276849	357043	374320	605411	395090
E07000004	Aylesbury Vale	192781	251989	278386	399072	286183
E07000005	Chiltern	95251	105464	107154	116044	116737
E07000006	South Bucks	69856	81121	83698	89772	92192
E07000007	Wycombe	175463	191736	195726	207144	215311
E07000008	Cambridge	124742	130222	174098	111787	262622
E07000009	East Cambridgeshire	88228	102448	107254	115049	121503
E07000010	Fenland	99677	116379	119314	132300	130184
E07000011	Huntingdonshire	176174	202223	218527	229321	229412
E07000012	South Cambridgeshire	156118	179582	209289	346547	228360
E07000150	Corby	68332	91966	95276.3	105203	104515
E07000151	Daventry	81145	93801	96361	104600	103457
E07000152	East Northamptonshire	91418	109315	111964	125029	119926
E07000153	Kettering	99001	119591	123613	136380	134972
E07000154	Northampton	224649	266402	274655	308259	335447
E07000155	South Northamptonshire	89908	106991	106890	113227	110174
E07000156	Wellingborough	78407	89862	92464	104429	98862
E07000177	Cherwell	146726	163505	194884	291011	193953
E07000178	Oxford	155423	161214	195845	202425	299786
E07000179	South Oxfordshire	139229	156783	165987	177692	189985
E07000180	Vale of White Horse	128728	150067	159537	167025	181333
E07000181	West Oxfordshire	108805	119337	125493	131383	144396

Table D3: Total land area developed in each scenario (ha)					
LAD Code	LAD Name	Baseline	Unplanned	New Settlements	Expansion
E06000031	Peterborough	1058	1216	1904	2417
E06000032	Luton	259	600	259	364
E06000042	Milton Keynes	1668	2848	3193	6817
E06000055	Bedford	1428	2241	2570	4339
E06000056	Central Bedfordshire	2602	3103	10562	3773
E07000004	Aylesbury Vale	2035	2845	6951	3110
E07000005	Chiltern	161	25	161	828
E07000006	South Bucks	87	21	87	1089
E07000007	Wycombe	481	659	1000	1243
E07000008	Cambridge	110	528	0	933
E07000009	East Cambridgeshire	649	865	1220	1514
E07000010	Fenland	673	769	1290	1205
E07000011	Huntingdonshire	1040	1708	2140	2144
E07000012	South Cambridgeshire	1055	2415	8600	3274
E07000150	Corby	819	897	1236	1213
E07000151	Daventry	638	709	1119	1063
E07000152	East Northamptonshire	633	679	1135	957
E07000153	Kettering	628	727	1114	1071
E07000154	Northampton	947	1145	1256	1256
E07000155	South Northamptonshire	757	722	1001	867
E07000156	Wellingborough	348	427	791	622
E07000177	Cherwell	654	1878	5621	1842
E07000178	Oxford	98	606	209	397
E07000179	South Oxfordshire	731	1131	1620	2132
E07000180	Vale of White Horse	852	1148	1443	2007
E07000181	West Oxfordshire	406	654	881	1383

Some scenarios allow development on the greenbelt. The total land lost in greenbelt areas in each scenario is given in Table D4.

Table D4: Total land developed in greenbelt areas				
Scenario	Baseline	Unplanned	New Settlements	Expansion
Greenbelt development (ha)	0	2159	475	12481

Appendix E: Urban form

Table E1: 'Centre' class of residential typology within the Arc area and its generic characteristics for tiles of 500m × 500m

Centre (345)	Building type	Total footprint area (m2)	Average footprint area (m2)	Site coverage (%)	Number of gardens	Garden area (m2)	Average garden area (m2)	Number of streets	Street lengths (m)	Average street lengths (m)	Street connectivity (number of nodes)
Mean	--	20854	103	8	485	55190	204	104	6831	77	126
St.dev.	--	13963	103	6	401	36849	346	66	2411	25	85
min	--	105	43	0	0	0	0	7	947	27	4
max	--	67502	1209	27	2244	146883	4917	510	15829	172	698
25% (percentile)	Semi-detached	10605	64	4	177	25431	74	60	5134	60	72
50% (percentile)	Terraced	18758	77	8	415	52312	114	91	6439	73	111
75% (percentile)	Terraced	28258	96	11	649	81789	203	128	8142	88	156

Table E2: 'Urban' class of residential typology within the Arc area and its generic characteristics for tiles of 500m × 500m

Urban (1630)	Building type	Total footprint area (m2)	Average footprint area (m2)	Site coverage (%)	Number of gardens	Garden area (m2)	Average garden area (m2)	Number of streets	Street lengths (m)	Average street lengths (m)	Street connectivity (number of nodes)
Mean	--	27492	73	11	657	102928	185	59	5156	98	76
St.dev.	--	7463	125	3	251	37781	150	39	1834	26	59
Min	--	8826	42	4	2	305	34	10	757	24	5
Max	--	61874	5040	25	1830	249062	2027	864	21016	255	1444
25% (percentile)	Detached	21826	58	9	484	73719	116	35	3885	79	43
50% (percentile)	Semi-detached	27423	65	11	628	102298	153	50	4771	94	63
75% (percentile)	Terraced	32628	75	13	801	127741	206	75	6124	112	95

Table E3: 'Suburban' class of residential typology within the Arc area and its generic characteristics for tiles of 500m × 500m

Suburban (3694)	Building type	Total footprint area (m2)	Average footprint area (m2)	Site coverage (%)	Number of gardens	Garden area (m2)	Average garden area (m2)	Number of streets	Street lengths (m)	Average street lengths (m)	Street connectivity (number of nodes)
Mean	--	8838	120	4	165	49561	655	31	2948	112	36
St.dev.	--	7878	465	3	163	42715	965	28	1650	47	41
Min	--	15	15	0	0	0	0	0	0	0	0
Max	--	48282	23147	19	1378	239990	10687	576	18692	912	900
25% (percentile)	Detached	2430	65	1	31	14176	190	15	1810	84	15
50% (percentile)	Detached	7272	81	3	123	38384	315	23	2687	103	26
75% (percentile)	Semi-detached	12900	110	5	252	75961	644	39	3788	132	47

Table E4 'Rural' class of residential typology within the Arc area and its generic characteristics for tiles of 500m × 500m

Rural (16042)	Building type	Total footprint area (m2)	Average footprint area (m2)	Site coverage (%)	Number of gardens	Garden area (m2)	Average garden area (m2)	Number of streets	Street lengths (m)	Average street lengths (m)	Street connectivity (number of nodes)
Mean	--	1289	133	1	20	14500	1467	7	1147	214	6
St.dev.	--	2357	113	1	42	18902	1566	6	665	110	7
Min	--	5	5	0	0	0	0	0	0	0	0
Max	--	31953	3433	13	901	182182	43049	85	6172	906	111
25% (percentile)	Detached	173	82	0	2	2547	598	3	667	139	1
50% (percentile)	Detached	408	109	0	5	6967	1034	5	1041	193	4
75% (percentile)	Detached	1242	149	0	17	18582	1804	9	1507	265	7

Table E5: Random Forests model performance – accuracy matrix				
	Centre	Urban	Suburban	Rural
Centre	16	17	7	0
Urban	3	119	9	0
Suburban	2	28	95	27
Rural	0	4	25	62

Table E6: Random Forests model performance – accuracy per class	
Centre	40.0%
Urban	90.8%
Suburban	62.5%
Rural	68.1%

Table E7: Random Forests model performance – test and training accuracy	
General Test accuracy	70.5%
General Train accuracy	96%
OOB score*	0.6648

* Out of bag (OOB) score is a way of validating the Random Forests model; it shows the accuracy/performance of the model in the training set. The OOB score is generally between 0 and 1, and the closer to 1, the greater the accuracy.

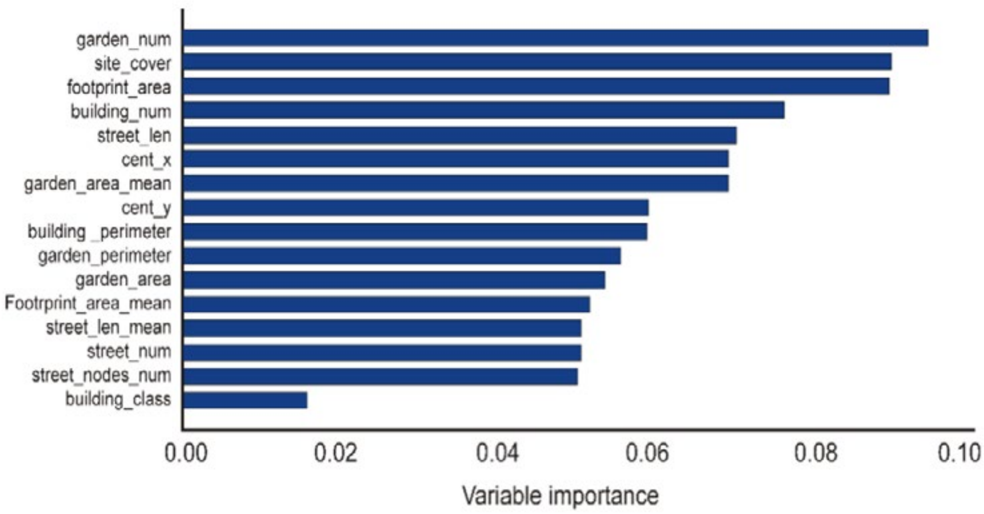

Figure E1 Variable importance. The graph shows the importance of each feature during the Random Forests training for the estimation of the classification of urban forms

Table E8: Residential typologies for the three scenarios of high, medium and low density (standard development), D (detached), S (semi-detached), T (terraced), F (flats)

	ID	Neighbourhood residential typology	Density (no of dwellings per 4h)	Total footprint area (m2)	Site coverage (%)	Domestic garden (%)	Green space (%)	Roads, paths, outdoor parking (%)	Total floor area (m2)	Floor area ratio	No of occupants (per 4h)
High density scenarios	1	D,S	144	7992	20	53	0	27	14340	0.36	312
	2	D,S,T,F	397	10075	25	30	7	38	24944	0.62	609
	3	T,F	650	12158	30	7	14	49	35548	0.89	906
Medium density scenario	1	D,S	108	6798	17	61	0	22	12008	0.30	261
	2	D,S,T,F	308	9519	24	38	3	35	20816	0.52	505
	3	T,F	508	12240	31	14	7	48	29624	0.74	749
Low density scenarios	1	D,S	42	3510	8	77	0	15	7020	0.18	153
	2	D,S,T,F	120	4921	12	60	6	22	11155	0.28	275
	3	T,F	198	6332	16	44	11	29	15290	0.38	397

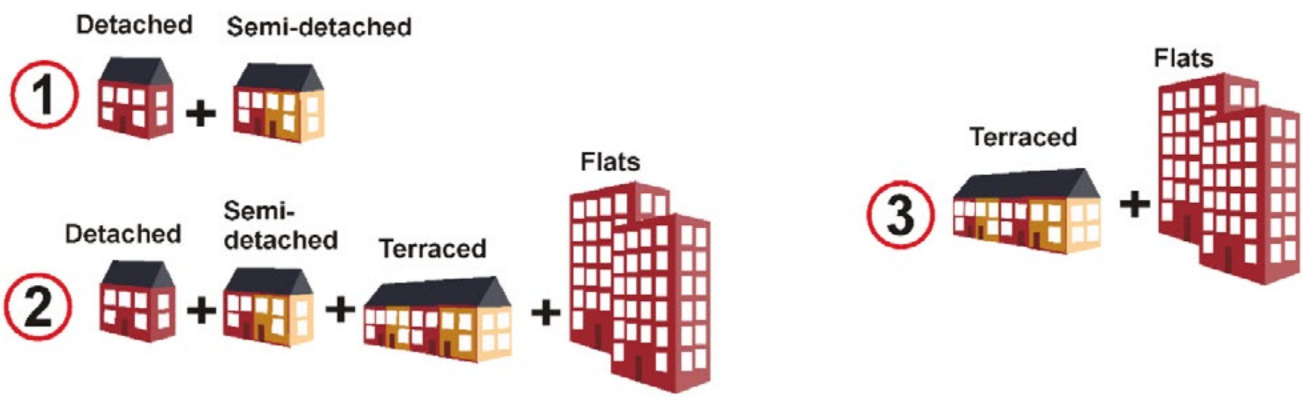

Figure E2 Schematic presentation of single building types: Detached, Semi-detached, Terraced and Flats. Different combinations of single building types are used for neighbourhood typologies

Table E9: Residential typologies for the four scenarios of very high, high, medium and low density (green development)

	ID	Neighbourhood residential typology	Density (no of dwellings per 4h)	Total footprint area (m2)	Site coverage (%)	Domestic garden (%)	Green space and green parking (%)	Roads, paths, outdoor parking (%)	Total floor area (m2)	Floor area ratio	No of occupants (per 4h)
Very high density scenarios	1	D,S	720	8360	21	20	34	25	48120	1.2	1293
	2	D,S,T,F	511	9575	24	22.25	21	32.75	34388	0.85	871
	3	T,F	878	11158	28	7.5	26	38.5	54436	1.36	1430
High density scenarios	1	D,S	144	7992	20	37	16	27	14340	0.36	312
	2	D,S,T,F	397	10075	25	22.5	21	31.5	24944	0.62	609
	3	T,F	650	12158	30	7.5	26	36	35548	0.89	906
Medium density scenario	1	D,S	108	6798	17	44	17	22	12008	0.3	261
	2	D,S,T,F	308	9519	24	29	18.25	28.75	20816	0.52	505
	3	T,F	508	12240	31	14	20	35	29624	0.74	749
Low density scenarios	1	D,S	42	3510	8	64.5	12.5	15	7020	0.18	153
	2	D,S,T,F	120	4921	12	54.25	14.25	19.5	11155	0.28	275
	3	T,F	198	6332	16	44	16	24	15290	0.38	397

Table E9: (cont.) Residential typologies for the four scenarios of very high, high, medium and low density (green development)

	ID	Neighbourhood residential typology	Optimal roof slope degree (gable, hip)	Available roof area, m2, for green roof and solar PV (Scenario 30%)	Available roof area, m2, for green roof and solar PV (Scenario 60%)	Available roof area, m2, for green roof and solar PV (Scenario 90%)
Very high density scenarios	1	D,S	38	1914	3828	5742
	2	D,S,T,F	38	2873	5745	8618
	3	T,F	38	3347	6695	10042
High density scenarios	1	D,S	38	2398	4795	7193
	2	D,S,T,F	38	3023	6045	9068
	3	T,F	38	3647	7295	10942
Medium density scenario	1	D,S	38	2039	4079	6118
	2	D,S,T,F	38	2856	5711	8567
	3	T,F	38	3672	7344	11016
Low density scenarios	1	D,S	38	1053	2106	3159
	2	D,S,T,F	38	1476	2953	4429
	3	T,F	38	1900	3799	5699

Appendix F: Green Infrastructure: matrix of ecosystem service scores for each habitat type

Habitat	Food production	Wood production	Fish production	Water supply	Flood regulation	Erosion protection	Water quality regulation	Carbon storage	Air quality regulation	Cooling and shading	Noise reduction	Pollination	Pest control	Recreation	Aesthetic value	Education	Interaction with nature	Sense of place	Biodiversity
Broadleaved, mixed and yew semi-natural woodland	1	6	0	3	9	10	10	10	6	10	8	7	8	10	10	10	10	10	8
Broadleaved, mixed and yew plantation	0	8	0	2	9	8	8	9	6	10	8	6	6	10	10	6	7	8	5
Native pine woodlands	0	0	0	3	9	8	6	7	8	10	10	6	8	10	10	10	10	10	8
Coniferous plantation	0	10	0	1	10	6	5	8	10	10	10	2	6	10	6	6	4	6	2
Wood pasture and parkland with scattered trees	5	2	0	7	6	8	6	5	3	6	6	7	8	10	10	8	8	10	10
Traditional orchards	5	1	0	7	8	8	5	5	4	8	6	7	8	8	10	8	7	10	8
Dense scrub	1	2	0	4	6	8	5	6	7	6	6	7	10	8	8	6	8	6	5
Hedgerows	1	1	0	4	6	8	5	5	8	6	6	8	10	8	10	8	10	10	10
Felled woodland	0	0	0	4	1	0	1	2	0	1	0	1	3	5	1	1	1	1	2
Tall herb and fern	1	0	0	8	8	8	5	4	1	2	1	7	10	8	10	6	8	4	3
Bracken	1	0	0	8	8	8	5	4	1	2	1	6	8	8	6	4	6	2	5
Semi-natural grassland	6	0	0	9	8	8	4	4	1	2	1	7	8	10	10	10	10	10	8
Acid grassland	6	0	0	9	8	8	4	4	1	2	1	6	8	10	10	10	10	10	8
Calcareous grassland	6	0	0	9	8	8	4	3	1	2	1	10	8	10	10	10	10	10	8
Neutral grassland	6	0	0	9	8	8	4	4	1	2	1	7	8	10	10	10	10	10	8
Improved grassland	10	0	0	7	3	4	1	3	1	2	1	2	3	5	4	2	2	4	2
Arable fields, horticulture and temporary grass	10	0	0	7	2	1	1	2	1	2	1	2	2	5	2	2	1	2	2
Arable field margins	0	0	0	8	4	6	5	2	1	2	1	6	8	10	8	6	6	4	6
Woody biofuel crops	0	10	0	3	4	2	1	4	1	2	1	2	4	5	2	2	1	2	5
Intensive orchards	10	1	0	3	8	6	1	5	4	8	6	6	4	5	8	2	1	2	2
Bog	1	0	0	10	5	8	7	10	1	4	1	4	3	8	8	8	10	10	10
Dwarf shrub heath	1	0	0	8	5	8	5	4	1	2	1	10	9	10	10	8	10	10	8

Habitat	Food production	Wood production	Fish production	Water supply	Flood regulation	Erosion protection	Water quality regulation	Carbon storage	Air quality regulation	Cooling and shading	Noise reduction	Pollination	Pest control	Recreation	Aesthetic value	Education	Interaction with nature	Sense of place	Biodiversity
Inland rock	0	0	0	0	0	0	0	0	0	0	0	0	0	8	10	10	6	10	8
Freshwater	0	0	10	10	0	0	1	1	0	4	0	1	2	10	10	10	10	10	8
Standing open water and canals	0	0	10	10	4	0	1	1	0	4	0	1	2	10	10	10	10	10	8
Running water	0	0	10	10	1	0	1	0	0	4	0	1	2	10	10	10	10	10	8
Fen, marsh and swamp	1	0	0	10	4	8	7	6	1	4	1	4	3	6	10	10	10	10	8
Lowland fens	1	0	0	10	4	8	7	6	1	4	1	4	3	6	10	10	10	10	10
Purple moor grass and rush pastures	4	0	0	9	4	8	7	4	1	2	1	4	6	10	10	8	10	10	10
Upland flushes, fens and swamps	1	0	0	10	4	8	7	6	1	4	1	4	3	6	10	10	10	10	8
Aquatic marginal vegetation	0	0	10	10	4	8	7	2	1	4	1	6	8	6	10	10	10	10	5
Reedbeds	0	0	10	10	4	8	7	4	1	4	1	2	3	6	10	10	10	10	8
Other swamps	1	0	0	10	4	8	7	4	1	4	1	4	3	6	10	8	10	10	5
Coastal rock	0	0	0	0	1	1	0	0	0	0	0	0	0	10	10	10	8	10	8
Coastal saltmarsh	4	0	10	2	5	8	6	4	1	4	1	3	3	6	10	10	10	10	10
Vegetated dunes and shingle	1	0	0	2	2	8	1	1	0	1	1	9	3	10	10	8	8	10	8
Beach and bare sand	0	0	0	2	2	6	0	0	0	0	0	0	2	10	10	8	6	10	2
Other littoral sediment	0	0	0	0	2	6	0	1	0	2	1	0	0	6	6	8	6	10	8
Sealed surface and buildings	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Artificial unvegetated, unsealed surface	0	0	0	4	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Bare ground	0	0	0	4	1	0	1	1	0	1	0	0	1	0	0	0	0	0	1
Garden	0	0	0	3	2	2	1	1	1	1	1	3	2	2	2	2	2	2	2
Vegetated garden	1	0	0	7	3	5	2	2	2	2	2	7	4	4	6	4	4	4	3
Unvegetated garden	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Open mosaic habitats on previously developed land	0	0	0	5	2	4	1	2	1	2	1	6	6	8	6	8	6	4	8

Habitat	Food production	Wood production	Fish production	Water supply	Flood regulation	Erosion protection	Water quality regulation	Carbon storage	Air quality regulation	Cooling and shading	Noise reduction	Pollination	Pest control	Recreation	Aesthetic value	Education	Interaction with nature	Sense of place	Biodiversity
Parks and gardens	0	0	0	7	3	5	2	4	3	4	2	6	8	10	8	6	6	6	5
Footpath / cycle path – green	0	0	0	5	2	3	1	2	1	2	1	4	4	10	6	2	4	6	2
Green bridge	0	0	0	5	2	1	1	1	1	2	1	2	2	10	6	6	8	8	10
Amenity grassland	0	0	0	7	3	4	2	3	1	2	1	2	2	10	5	2	2	2	2
Road island / verge	0	0	0	5	3	4	2	3	1	2	1	2	2	2	5	2	2	2	2
Natural sports pitch, recreation ground or playground	0	0	0	7	3	3	2	3	1	2	1	2	2	10	2	2	2	4	2
Cemeteries and churchyards	0	0	0	7	3	4	2	4	2	2	1	6	4	2	6	2	4	8	5
Allotments, city farm, community garden	7	0	0	7	2	1	1	3	2	2	2	8	4	10	5	6	4	10	5
Intensive green roof	0	0	0	0	3	1	1	2	1	6	1	6	4	2	5	4	4	6	3
Green wall	0	0	0	0	1	1	1	1	4	6	2	6	4	0	6	4	2	6	2
Brown roof or extensive green roof	0	0	0	0	1	1	1	1	1	2	1	6	8	2	4	4	4	6	5
Tree	0	1	0	1	6	6	2	7	6	8	6	6	8	2	10	8	8	10	5
Bioswale	0	0	0	5	5	2	2	2	1	4	1	5	4	2	8	4	6	4	2
Rain garden	0	0	0	10	5	2	7	2	1	4	1	6	6	2	10	6	8	6	3
Introduced shrub	0	1	0	4	5	6	4	4	4	6	6	6	6	2	8	2	4	4	2
Flower bed	0	0	0	7	2	2	1	2	1	2	1	6	6	2	10	2	6	4	5

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