Progressive energy

Green City Vision

Technical Report

Report for Wales & West Utilities, UK Power Networks and Scottish & Southern Electricity Networks

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Version Control Table

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V 0.2	22/04/2019	Tommy Isaac	Second draft for consortia review
V 0.3	24/05/2019	Tommy Isaac	Third draft for sign off
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EXECUTIVE SUMMARY

Decarbonisation of the energy system supplying any region such as Swindon (SN) will require significant change. The goal of achieving an 80% reduction in carbon emissions by 2050 relative to 1990 requires balancing available technologies and options to minimise system disruption and cost to consumers. The strategic objective of the Green City Vision project was to understand the system implications of applying alternative decarbonising strategies, to illuminate system trade-offs and insights, and to establish a potential 'optimum' solution based on the modelling methodology undertaken.

The Pathfinder modelling demonstrated a range of solutions that could be employed to achieve compliance – as defined as a system in which energy supply meets energy demand at all points throughout the year whilst achieving overall emissions targets. The main outcomes from the analysis undertaken are:

1) The scenarios modelled indicated that continued operation of both the gas and electricity network will provide the least disruptive pathway to compliance – as evidenced from the necessary investment implications and changes that resulted from the single-vector Electrification and Green Gas scenarios (Section 7.5 and Section 8.5 respectively);
2) All decarbonisation vectors have their role to play, however to achieve a given level of carbon emissions reductions, 'top down' supply-driven strategies were determined to be more deliverable than 'bottom up' demand-driven strategies. An example of such deliverability is detailed in Section 15.3 where, in a 2050 energy system, a 10 MW biomethane plant would yield the same decarbonisation as 8000 ASHPs, and would require 45% less subsidy to incentivise the same decarbonising output, at current support prices;
3) The expected adoption of electric vehicles (minimum 90% of cars and vans by 2050) alone will require investment to facilitate a resulting compound peak demand growth rate of 5% each 5-year RIIO period until 2050 (Section 6.4). Therefore, the delivery of further decarbonisation will be made more achievable by leveraging the gas network to achieve compliance, given that a full Electrification compliance scenario yielded an 11% compound peak demand growth rate each 5-year RIIO period until 2050 (Section 7.5);
4) The decarbonisation of heat is a necessary condition for compliance given that current Swindon heat emissions are 15% greater than the 2050 total emissions target (Section 6.2). Focusing on low-carbon gas, supported by efficiency improvements and hybrid heat pumps, followed by other measures, is seen as the least disruptive pathway to compliance, given the advantages of leveraging the gas network and the deliverability advantages of supply-driven strategies over demand-driven strategies;
5) Integrated demand forecasting between the gas and electricity network will be essential in ensuring reliable supply to the collective energy system. Particularly with reference to gas network diurnal storage – as flexible capacity for electric vehicle charging will dominate gas demand in the summer months, where

generation requirements will be determined by the availability of intermittent renewable electricity;

6) Consumer choice will play a major role in achieving compliance, given that maximising energy efficiency to the technical upper limit could reduce overall emissions by 28% (Section 6.6) and optimising electric vehicle charging patterns could reduce additional peak demand by up to 15% (Section 15.2). Therefore, incentivisation of consumer investment will be an important factor in determining the ultimate compliance pathway;
7) Based on the scenarios modelled, the average reduction in both annual and peak gas demand by 2050 was 35% (Section 14.2), relative to current operation, which is in line with an average reduction of 32% across the National Grid future energy scenarios by 2050[29];
8) The main investment foci for the gas network within the SN area should be; facilitation of at least 80 MW of biomethane capacity (Section 13.5) along with investment in hydrogen transmission infrastructure, as well as investment to reduce opex and ensure a low-cost operation in a reduced utilisation environment;
9) Based on the scenarios modelled, the average increase in annual and peak electricity demand by 2050 was 50% and 45% respectively (Section 14.3), relative to current operation;
10) Annual average electricity generation inertia is forecast to reduce from 70% to 50% by 2050 (Section 14.3), which is broadly in line with the 2018 National Grid future energy scenarios which on average yield 40% inertia by 2050[30]. The minimum-inertia hour calculated from the scenarios modelled was 20%;
11) The main investment foci for the electricity network within the SN area should be; regional investment to facilitate a minimum compound peak growth rate of 5% each 5-year RIIO period, as well as investment to accommodate a much more dynamic system given that the average increase in peak demand change rates was found to be 60% (Section 14.3).

The technical tool used to analyse the scenarios modelled was the Pathfinder model. More detail on the model is provided in Section 3.0. The modelling methodology employed consisted of:

1) Defining a reference point for the SN energy system in 2050, based on 2018 National Grid Future Energy Scenario (FES) data;
2) Applying a decarbonisation strategy to this reference scenario until compliance was achieved;
3) Analysing the calculated actions necessary to achieve compliance from each scenario; followed by,
4) Undertaking an overall comparison of necessary conditions for compliance between all scenarios to inform decarbonisation strategy recommendations.

The decarbonisation strategies were defined as being either ‘top down’ supply-driven or ‘bottom up’ demand-driven. Starting with single-vector strategies and incrementally introducing more decarbonisation levers to quantitatively understand the system advantages of applying holistic decarbonisation strategies. The following table outlines the scenarios modelled and their rationale.

Table 1-1: Scenarios Modelled

Strategy	Scenario	Description	Reference
N/A	**Reference**	Baselining a possible 'status-quo' of the SN area in 2050, based on 2018 National Grid FES.	Section 6
Supply-Driven	**Electrification**	Achieving compliance by solely leveraging low-carbon electricity use.	Section 7
Supply-Driven	**Green Gas**	Achieving compliance by solely leveraging low-carbon gas use.	Section 8
Supply-Driven	**Supply-Hybrid**	Achieving compliance by balancing the deployment of low-carbon electricity and low-carbon gas, minimising disruptive impact where possible.	Section 9
Demand-Driven	**Consumer Led**	Achieving compliance by consumers taking full ownership via modifying behaviour and personal investment.	Section 10
Demand-Driven	**Business Led**	Achieving compliance by businesses taking full ownership via modifying behaviour and investment.	Section 11
Demand-Driven	**Demand-Hybrid**	Achieving compliance by balancing the modification of consumer and business behaviour as well as investment, minimising disruptive impact where possible.	Section 12
Combined Supply and Demand-Driven	**Multi-Vector**	Achieving compliance by balancing supply-driven and demand-driven approaches, maximising low-regrets solutions and highlighting engineering trade-offs.	Section 13

What was evident from all the scenarios modelled was that, achieving compliance will require fundamental change in the energy landscape and necessitate investment. The deployment of smart solutions can be utilised to reduce the necessary level of investment required to achieve compliance. An example is the deployment of smart electric vehicle charging, which was found to reduce the additional peak demand on the electricity network from electric vehicle charging by 15%. However, this still left 85% of the additional peak demand needing to be accommodated.

Therefore, to achieve compliance utilising the lowest-cost pathway, rigorous whole-system analysis should sit at the centre of decarbonisation policy. This is to ensure the necessary investment required to achieve compliance is minimised. Leveraging the characteristics of both the gas and electricity network, to deploy synergistic technologies, will allow the lowest-cost compliance pathway to be implemented.

Meeting emissions targets within the Swindon area and nationally will ultimately be dependent on both local and national policy. Development of appropriate incentive programmes and mechanisms to promote the required action will need to be policy led. For example, the adoption of EVs is driven both by national decarbonisation policy and local health policy. Local and national policy frameworks must be aligned, informed by impartial analysis, and capable of promoting the magnitude of change required – this will be fundamental to successfully meeting emissions targets within the Swindon area and nationally.

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GLOSSARY OF TERMS

ASHP	Air Source Heat Pump
CCGT	Closed Cycle Gas Turbine
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
Consumers	Domestic energy consumers
DfT	Department for Transport
DNO	Distribution Network Operator
EV	Electric Vehicle
FES	Future Energy Scenarios
GDN	Gas Distribution Network
H-ASHP	Hybrid Air Source Heat Pump
HP	Heat Pump
ICE	Internal Combustion Engine
$MtCO_{2eq}$	Million Tonnes of Carbon Dioxide Equivalent
NIA	Network Innovation Allowance
OCGT	Open Cycle Gas Turbine
Ofgem	Office of Gas and Electricity Markets
Opex	Operational Expenditure
PEL	Progressive Energy Ltd
RHI	Renewable Heat Incentive
RIIO	Revenue = Incentives + Innovation + Outputs
SSEN	Scottish & Southern Electricity Networks
SN	Swindon
TOUT	Time of use Tariff
UK	United Kingdom
UKG	United Kingdom Government
UKPN	UK Power Networks
WWU	Wales & West Utilities

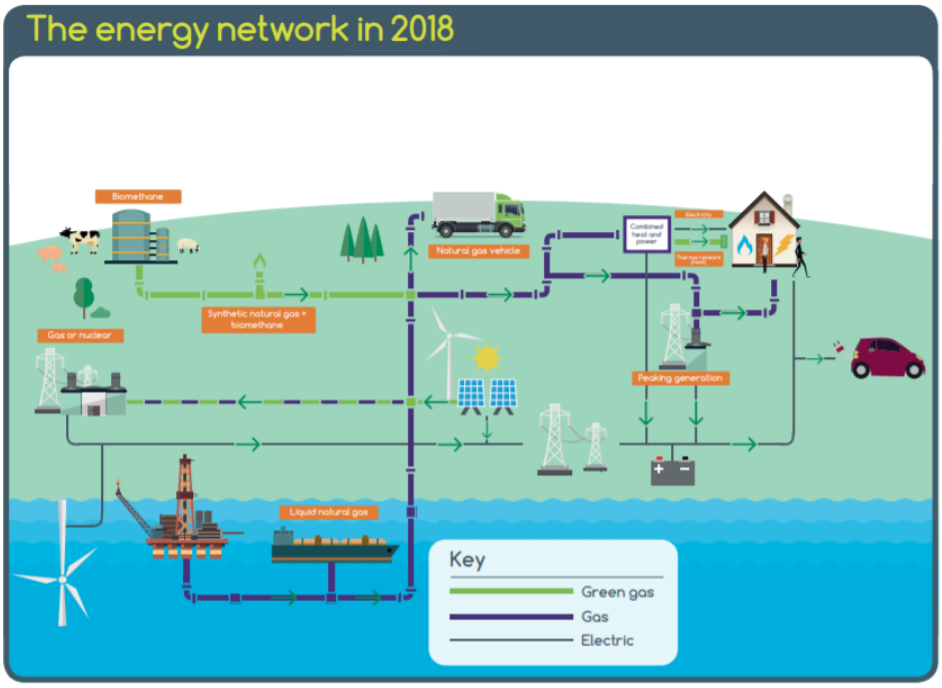
1.0 INTRODUCTION

Green City Vision is a collaborative project funded via the Ofgem Network Innovation Allowance (NIA). The project partners consist of:

1) Wales & West Utilities: Gas Distribution Network;
2) UK Power Networks: Distribution Network Operator;
3) Scottish & Southern Electricity Networks: Distribution System Operator; and
4) Progressive Energy: Low-carbon energy project developer and consultancy.

The purpose of the Green City Vision project is to create the initial evidence base to better understand system decarbonisation within the context of an integrated gas-electricity system. A number of decarbonisation strategies have been applied to a reference scenario to understand the requirements of any given strategy to achieve compliant region with respect to the UK's carbon emissions reduction target of 80% relative to 1990 by 2050.

Figure 1-1: UK Energy System



To date, analysis of the implications of decarbonising technologies and solutions have tended to focus on a single network. As the UK's energy systems have become more deeply decarbonised, they have also become more complex and interlinked. The structure of both the gas and electricity networks as isolated, top down infrastructure, is being challenged by the drive for decarbonisation. Both systems are becoming more fluid as a greater level of generation sources are connecting to the distribution networks, such as biomethane plants and embedded wind farms. The two systems are also becoming more integrated, as decarbonising technologies impact upon each, such as gas-fired flexible generation. The objective of the Green City Vision project is therefore to view decarbonisation strategies from a wider, more holistic perspective, by understanding the implications of any given strategy on the both the gas and electricity systems and focusing on the interface between the two. By integrating both supply-based and demand-based solutions across both networks, the outcome of Green City Vision project is to understand an optimum solution for decarbonisation with feasibility level investment implications to achieve such a solution.

The technical analysis for the project has been conducted using the Pathfinder model – an hourly energy system model created by WWU and Delta-EE. More detail on Pathfinder can be found in Section 3.0. The analysis consisted of mapping the current energy needs (heating, power and transport) of Swindon and the surrounding area. From this initial profiling a 2050 reference position was generated to frame the likely energy landscape for Swindon in 2050, utilising the Steady Progression scenario from National Grid's Future Energy Scenarios (FES) – which was deemed the most likely scenario of the four FES scenarios to constitute a 'status-quo', however is still itself ambitious in some respects. From this reference point a number of decarbonisation strategies were applied to understand how to generate a compliant region. The decarbonisation scenarios started as single vector solutions and then hybridised vectors to demonstrate the system benefits of multi-vectored solutions. The scenarios were split between:

1) **Supply-based**: Top-down strategies, focusing on national infrastructure and energy generation assets; and,
2) **Demand-based**: Bottom-up strategies, focusing on individual users and personal choice.

More detail on the scenarios can be found in Section 5.0. Once each scenario had achieved compliance, an analysis of the implications for consumers, the gas network, and the electricity network was undertaken.

2.0 SWINDON ENERGY PROFILE

2.1 2050 UK Reference Point

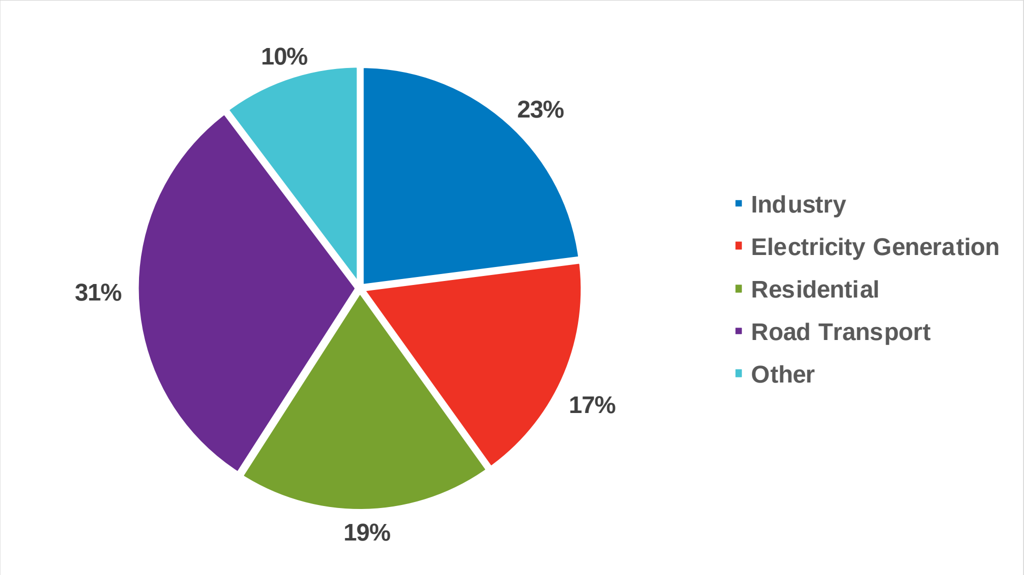
To model the implications of decarbonisation strategies for the Swindon area in 2050, it was incumbent to generate a UK 2050 reference point, from which each decarbonisation strategies could be applied to achieve compliance. The UK 2050 reference point chosen was the Steady Progression FES produced by National Grid. The accompanying data workbook published by National Grid was reviewed and the 2050 figures for the chosen scenario were translated into Pathfinder inputs to create a 2050 UK reference point.

Once the inputs for Pathfinder were translated from the workbook, a process of scenario refinement took place to align the total gas and electricity usage calculated by Pathfinder to the totals specified in the workbook. This process ensured that the 2050 UK reference point, as calculated by Pathfinder, was accurate and in agreement with the National Grid scenarios.

2.1.1 Current Energy Landscape

Energy generation and consumption data provides useful insight into the current distribution of energy use and resulting emissions. Total carbon dioxide emissions in 2017 were 351 $MtCO_2$[16] along with a further 109 $MtCO_{2eq}$[16] emissions from other sources to give a total emissions figure of 460 $MtCO_{2eq}$. The breakdown of the 351 $MtCO_2$ is given below.

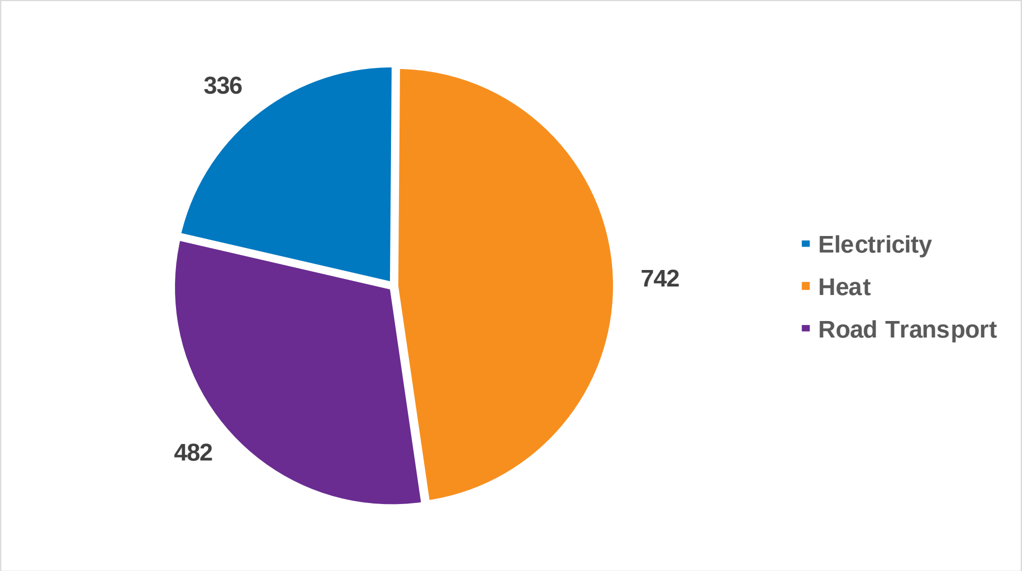
Figure 2-1: 2017 UK Carbon Dioxide Emissions Breakdown



By consumer group, road transport was the largest emitter of carbon dioxide. However, by energy source natural gas was the greatest due to natural gas being the dominant energy source in the other categories, namely; industry; residential; and, electricity generation.

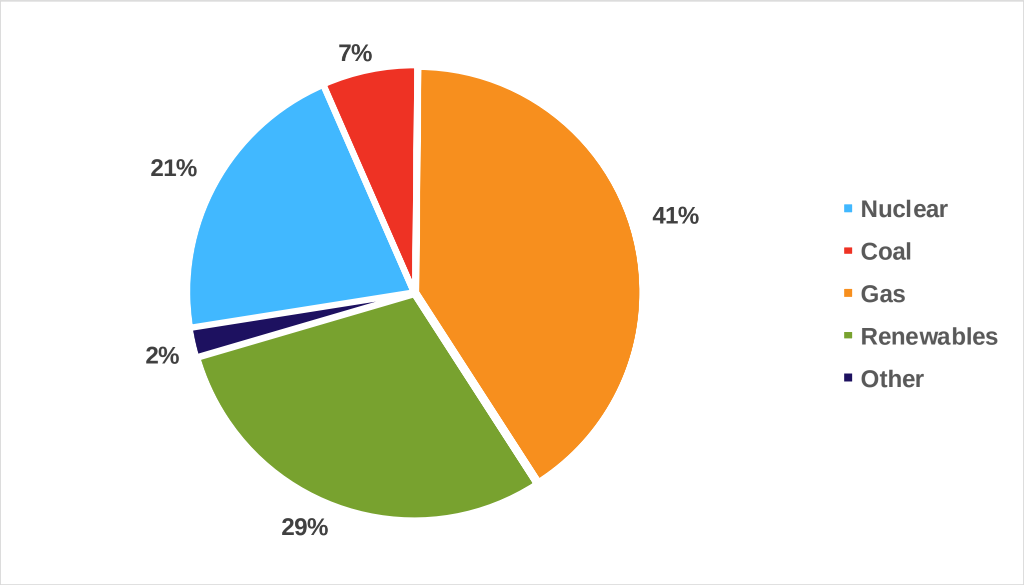
The total energy consumption across electricity, heat and road transport within the UK in 2017 was 1,560 TWh. The breakdown between these three categories is given below[17-19].

Figure 2-2: 2017 Energy Use Breakdown (TWh)



Heat was the single largest use of energy in 2017 with 48% of total energy use. Natural gas used in the production of electricity is captured within the 336 TWh electricity figure. By energy demand, road transport was 50% greater than electricity demand and heat was 130% greater. The generation mix breakdown of the 336 TWh of electricity demand by source in 2017 is given below[17].

Figure 2-3: 2017 Electricity Generation Mix



Natural gas provided the majority of electricity generation and renewable generation constituted 29% of electricity generation, of which wind made the largest contribution[17]. Figure 2-3 demonstrates the current high level of integration between the gas and electricity network, given that gas supplied 41% of the electricity generation to the UK in 2017.

2.2 Swindon Energy System Modelling

2.2.1 Why Swindon

The Swindon region was defined as all postcodes beginning with SN, which encompass Swindon town and the surrounding rural area, yielding a good mixture of demographics. The Swindon region in 2017 had a population of around 480k[20] which makes the Swindon region an appropriate size for Pathfinder modelling. The mixture of a large metropolitan town with rural surroundings provides a good basis for UK regional modelling.

The Swindon region is supplied with electricity from SSEN and gas from WWU, therefore access to demand and operational data could be achieved to allow accurate modelling of the region's energy demands.

2.2.2 2050 Regional Reference Point

Following generation of the 2050 UK reference point, the scenario was scaled to the Swindon area. The Swindon area was defined as all postcodes within the SN region, of which Swindon town accounts for 50% by population. The three scaling factors used to transform UK data to SN data were:

1) Population/household ratio between SN and UK;
2) Per capita national averages such as vehicle ownership; and
3) Energy demand ratio between SN and UK.

EU population projections, along with the 2011 UK census, were used to determine an estimate of the total population within the SN area in 2050. The 2011 census indicated that the occupancy of households within the SN area was equal to the UK average. Combining these two figures provided the estimate the number of households within the SN area in 2050.

The forecasted installed capacities of electricity generation within the SN area were estimated by multiplying the UK installed capacities of each generation source by the percentage of national electricity usage within the SN area. This scaling factor resulted in the overall carbon intensity of the electricity used within the SN area to be equal to the national average, which confirmed the validity of the methodology.

The number of estimated vehicles within the SN area was taken as the forecasted national average of registrations per capita, multiplied by the population. Department for Transport (DfT) figures of vehicle registration per postcodes indicate that the frequency of vehicle registration within the SN area, per capita, is 70% greater than the UK average. The dominant reason for this being the number of HGVs registered within the area for commercial purposes, given the central location of the SN area within the UK.

The rationale for using the UK average instead of the SN figure was due to the lack of data to show where each vehicle refuelled and emitted. For example, a national company could have all company cars registered to a single address, but distribute them across regional branches. Therefore, to ascribe the resultant emissions of those vehicles to the registration postcode could be unrepresentative.

The UK average heating profile, by technology, for domestic homes was taken as being representative of the SN area. The reason being that the frequency of gas connections of households within the SN area, based on WWU data, was found to be comparable to the UK average. Therefore, given the lack of data for off-grid households within the SN area, the UK average profile was applied to the SN area.

The last two parameters that were required to allow the 2050 SN reference point to be generated was the split of electricity and gas usage between domestic and non-domestic users. WWU data on the connection capacities of all users within the SN area was utilised to understand the split of gas use - the total domestic connection capacity was divided by the total connection capacity in the SN area, to provide a proxy. SSEN data on substation operation within the SN area was utilised to determine the split of electricity use – the power delivered through substations mainly feeding households was divided by the total power consumption to provide a proxy for electricity use split.

Once each of the above methodologies generated scaling and profiling factors for the SN area, they were applied to the UK 2050 reference point to generate the SN 2050 reference point. Both the UK and SN reference points were non-compliant with regards to emissions reductions – indicating that further decarbonisation via the implementation of a reduction strategy would be required. Further information on the SN carbon target used to determine compliance can be found in Section 4.0.

2.3 Characterisation of Existing Networks

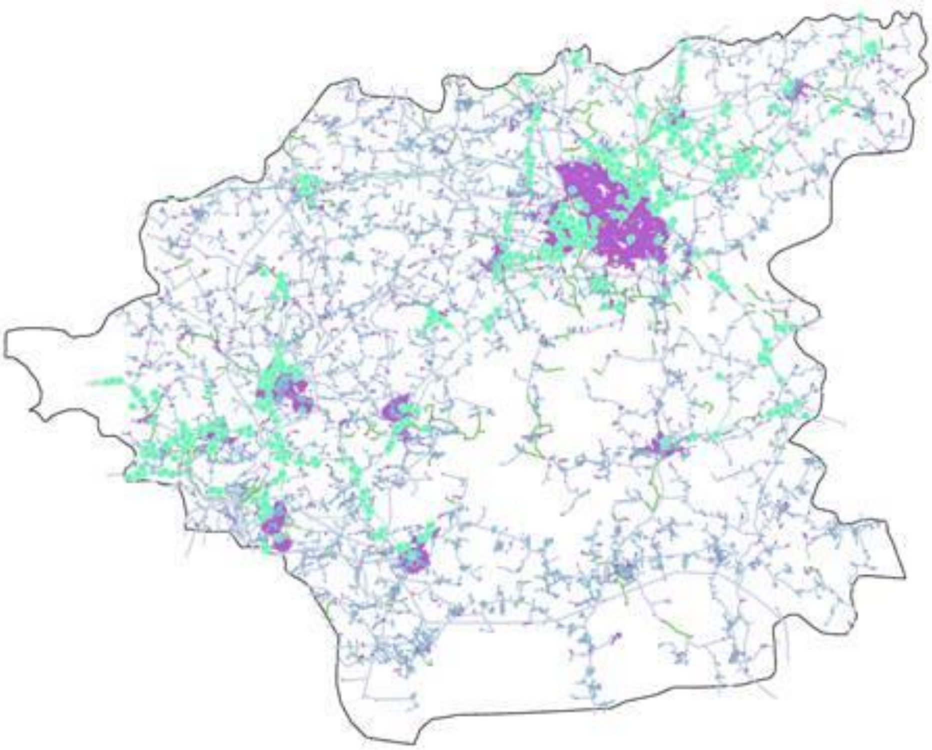
2.3.1 Swindon Gas Network

Gas is distributed to the Swindon area via the WWU network, the consumers of gas in the Swindon area span domestic, commercial and industrial users. Based on WWU data the proportion of properties connected to the grid within the Swindon area is 91%, which is the UK average based on the same dataset. The gas split of connection capacity between users in the Swindon area is as follows:

- Domestic – 65%;
- Commercial – 25%; and
- Industrial – 10%.

The proportion of industrial gas usage is less than the UK average, primarily driven by the lack of heavy industry in the Swindon area. The layout of the gas networking supplying the Swindon area is typical of gas networks, as presented in Figure 2-4.

Figure 2-4: Swindon Gas Network



Although gas supply in the region is dominated by traditional natural gas there are examples of local green gas projects, including AD plants and a demonstration Bio-substitute natural gas (BioSNG) plant.

2.3.2 Swindon Electricity Network

Electricity is distributed to the Swindon area by the SSEN network. As per the gas network, it supplies consumers spanning domestic, commercial and industry. The supply of electricity is primarily through large generation assets which provide electricity to via the transmission and distribution networks; however, a number of embedded low-carbon generation assets exist within the Swindon area, such as a 60 MW solar farm. There is also a proposed 50 MW battery storage installation within the Swindon region. Within the Swindon area 13 substations supply the majority of demand. Figure 2-5 shows the average hourly duty in 2017 of each substation as a proportion of their maximum capacities.

Figure 2-5: Swindon Substations

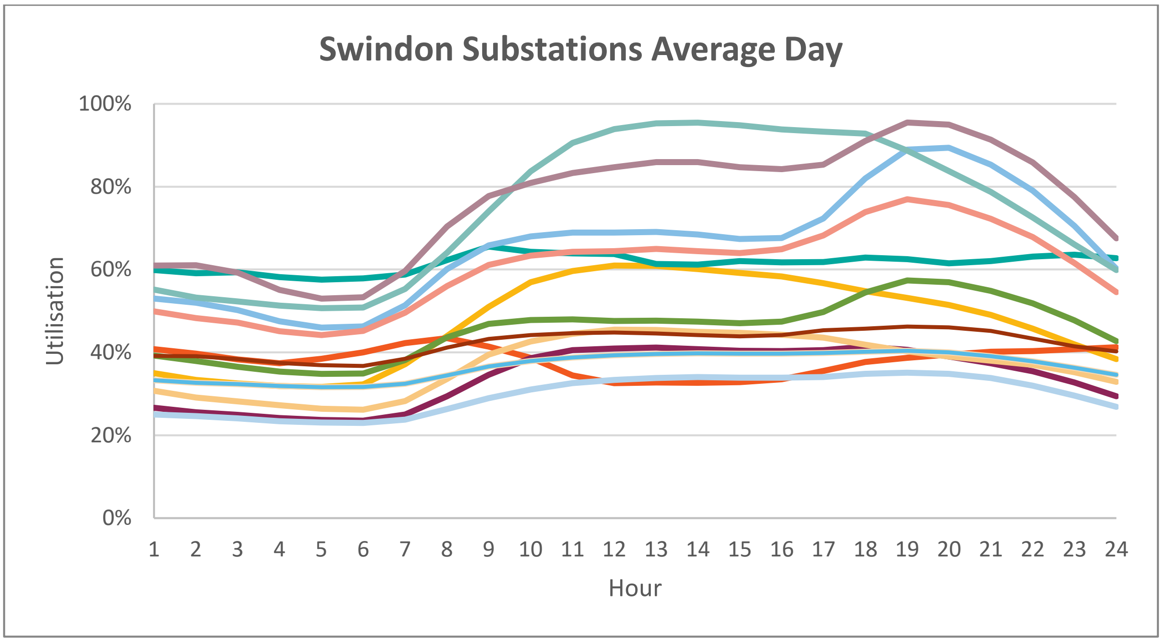


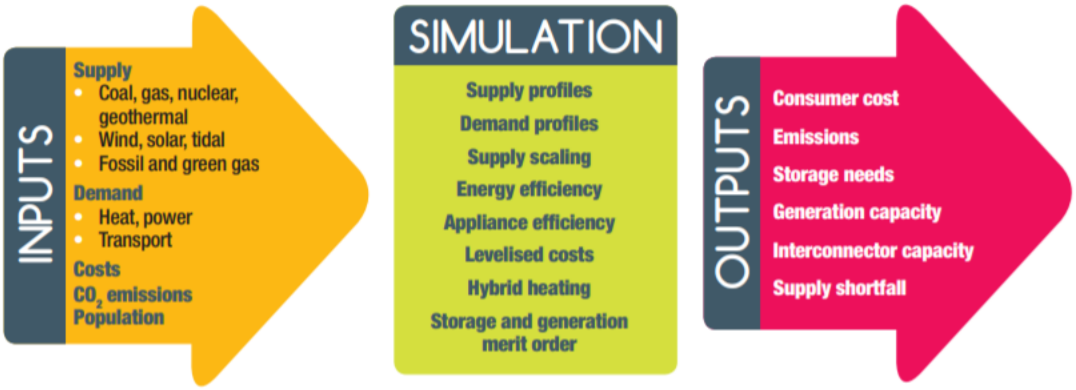
Figure 2-5 includes both 132/33kV substations as well as 33/11kV substations and spans all users within the Swindon area. There is a high degree of variation in the average loading of substations within the region, with peak loading generally experienced during the evening domestic peak period. Figure 2-5 demonstrates the complexity of reinforcement programme management, in that reinforcement scheduling is a function of both forecasted load and geographical distribution.

3.0 PATHFINDER MODEL

3.1 Model Summary

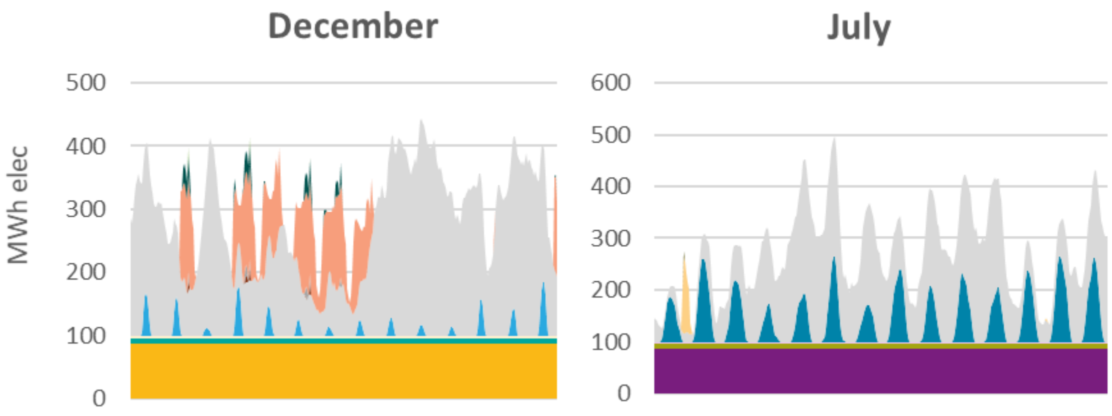
The Pathfinder model was developed by WWU in collaboration with Delta-EE. The model is a highly sophisticated engineering tool which allows the hourly balance of supply and demand across the gas and electricity network to be viewed, over the course of a year. Pathfinder takes account of the direct inputs to, and outputs from, each network, for domestic users, commercial users and any transport. This balancing of supply and demand is carried out predominately within the electricity network, given the large variety of generation sources available. An overview of the model is presented in Figure 3-1.

Figure 3-1: Pathfinder Model Overview



The purpose of the model is to allow the user to understand how both the electricity and gas networks would operate given a defined scenario, along with the interface between the two networks. Pathfinder's sophistication allows the user to target periods within the year of particular interest, such as the winter months for peak gas demand, or the summer months for peak solar supply. By specifying the periods of interest, Pathfinder will then generate 2-week charts to graphically represent the energy balancing process on an hourly basis. Figure 3-2 provides examples of such charts.

Figure 3-2: Electricity Supply Curves



The outturn results of the model principally indicate the overall emissions arising from the balancing of supply and demand across both networks, and if there are any periods in the year where blackouts could occur due to demand exceeding supply on the electricity network. A basic cost model is also included within the analysis; however, the overarching value in the model is in the technical insight it provides when assessing the system implications of any given energy strategy.

3.2 Green City Vision Adjustments

A number of adjustments and modifications to the Pathfinder model were performed throughout the Green City Vision project to create additional functionality. The modifications carried out to yield either greater insight or functionality where:

1) A bolt-on emissions calculation for vehicles with an Internal Combustion Engine (ICE) was generated. This allowed each scenario to take account of traditional forms of road transportation and quantify their effect on the overall emissions profile of the chosen area;
2) A natural gas blending tool was created for hydrogen and biomethane. This tool allowed the user to specify a production quantity of bulk hydrogen and biomethane, followed by blending the low carbon gases with natural gas. The resultant carbon intensity of the blended gas then fed into the emission model for domestic heating, commercial heating, CNG transport and gas-based power production;
3) An hour-by-hour inertia calculation was created to determine the proportion of electricity generation with associated mechanical inertia. The inertia of mechanical generation devices is the principal determinant of grid stability as the inertia acts like a shock absorber for frequency control. This tool therefore allowed the user to understand the potential frequency control implications of any mix of generation capacity on an hourly basis;
4) A peak shaving tool was developed to allow the user to specify a reduced proportion of peak domestic electricity demand and transfer that demand to

overnight usage. This functionality provided the ability to understand the aggregate effects of peaking shaving via consumer behaviour change or tariff incentives; and;

5) A modification to the calculation methodology of ASHP usage to take account of the required lead time necessary for the system to heat up. This analysis was indicative to account for warm up times.

Alongside these additional tools a number of calculations based on Pathfinders output were created to give greater insight into the scenario being modelled. For example, the load factor of flexible generation was incorporated as a bolt-on calculation.

Following the above modifications and adjustments to Pathfinder, each scenario was then able to fully model the transport, gas and power needs of the SN area whilst gaining greater insight into the system implications of each scenario.

4.0 CARBON TARGET

4.1 UK Carbon Target and Scope of Pathfinder

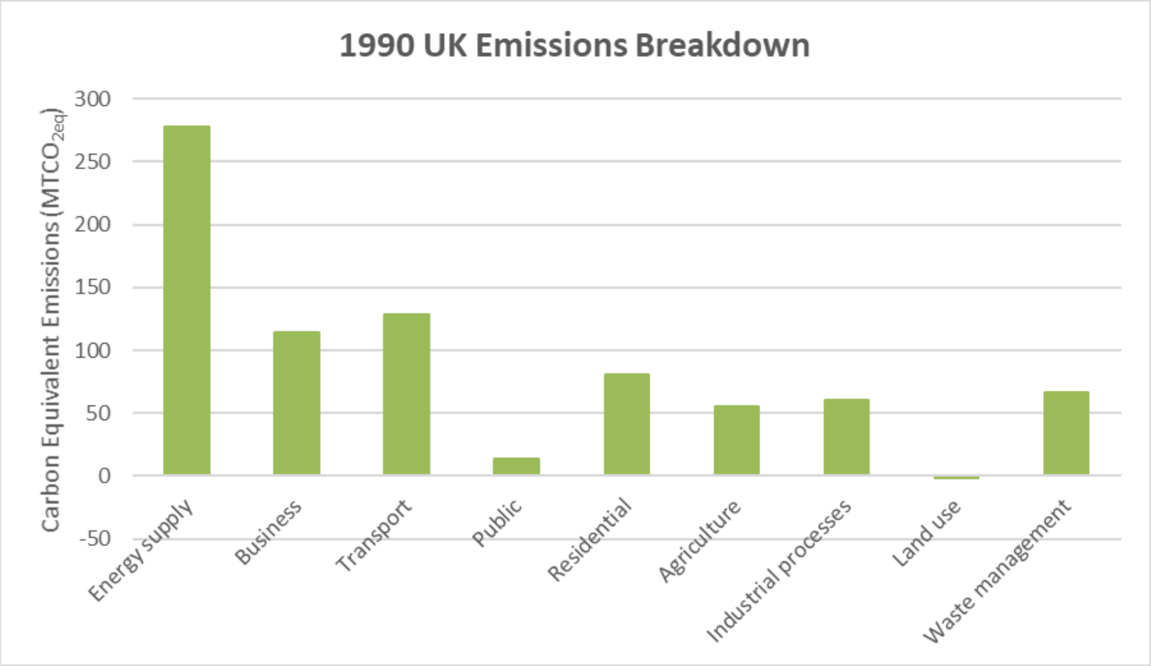
The 2008 Climate Change Act mandated a legally binding carbon emissions reduction target of 80% relative to 1990 by 2050. This target is to be achieved via carbon budgets, which provide intermediate reduction targets in 5-year increments, building towards the 80% reduction. The current reduction level achieved is 43% relative to 1990, as per the 2018 Climate Change Committee (CCC) Progress Report[1]. To date this reduction has been achieved through:

1) Replacement of coal-fired power stations with low-carbon alternatives such as gas, wind and biomass; and
2) Deindustrialisation, as the economy has become more services-focused, with significant manufacturing being ‘off-shored’.

The effect of replacing coal-fired power stations with low-carbon alternatives has been dramatic within the electricity market, as the average carbon intensity of electricity has halved over the period to 2013 – 2017[2].

The UK’s total emissions in 1990 were 794 $MtCO_{2eq}$[3], therefore the UK target for emissions in 2050 is 160 $MtCO_{2eq}$. The following provides a breakdown of the UK emissions in 1990.

Figure 4-1: 1990 UK Emissions Breakdown



It can be seen from the above that there are a number of emissions sources which are unrelated to the scope of calculation within Pathfinder, such as; agricultural emissions; waste management emissions; and land use.

The emissions that Pathfinder models are those associated with:

1) Power generation;
2) Commercial heat and power;
3) Road transport; and
4) Domestic heating.

In 1990 the above four categories of emissions totalled 510 $MtCO_{2eq}$. A compliant 2050 UK scenario, as modelled by Pathfinder, would result in calculated emissions equal to 20% of the 1990 UK figure – 102 $MtCO_{2eq}$. assuming emissions reductions were spread evenly across the economy in line with the ratio of emissions in 1990.

The four areas that pathfinder models equated to 64% of the total UK emissions in 1990. It is assumed that if a scenario modelled by Pathfinder can achieve compliance, then the total emissions profile is compliant. In practical terms, this would equate to separate policies and strategies to tackle the 36% of emissions not calculated by Pathfinder. However, it is assumed that these policies would be created and their implementation successful.

4.2 SN Carbon Target

The carbon target for the SN area in 2050 was formulated by scaling the UK target for Pathfinder emissions (102 $MtCO_{2eq}$) based on populations and per capita emissions within the SN region.

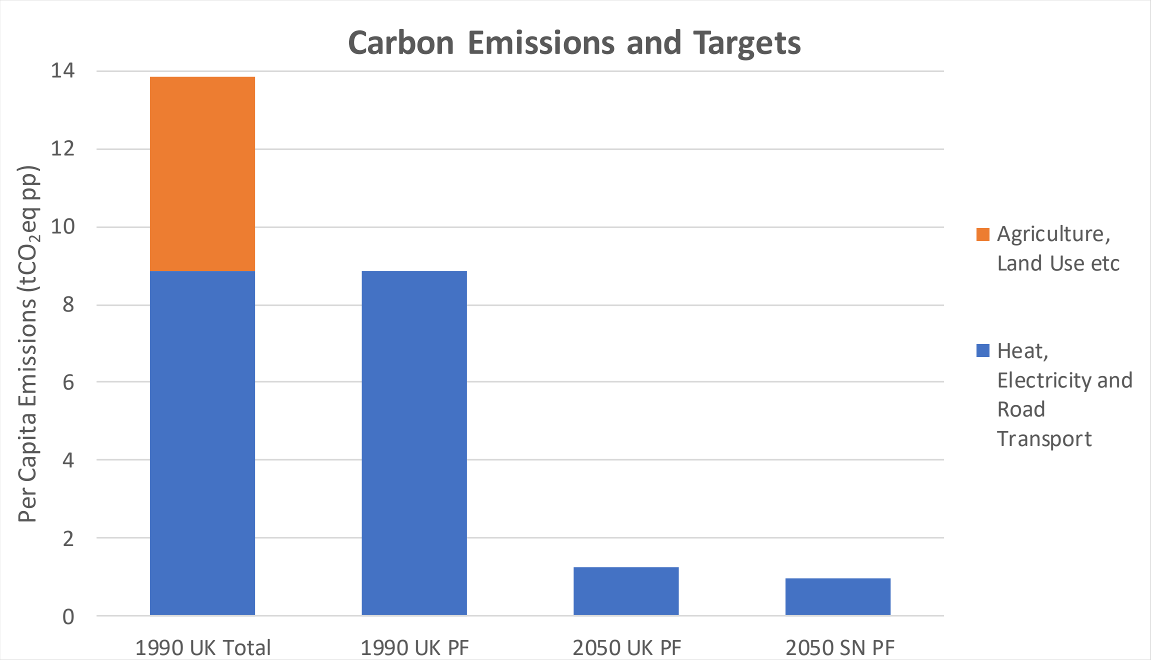
The UK Government (UKG) published in 2014 a review of region emissions from 2005 – 2012[4]. The average emissions from a resident in the SN area over the course of this period, inclusive of transport, domestic and commercial/industrial emissions, was 7.7 tCO_2pp. The average UK residents' emissions over the same period, based on UKG total emissions data and population figures, was 10 TCO_2pp. Therefore, the per capita emissions over of a resident in the SN area was 77% of the average UK resident. The primary reason for this difference being the lack of heavy industry within the SN area. Data from the 2011 UK census indicates that the proportion of UK nationals living within the SN area was 0.7% of the total population.

The 2050 emissions target for the SN area was calculated using the formula:

$$SN\ Target_{2050} = UK\ Target_{2050}\ x\ Population\ Fraction\ x\ Emissions\ Fraction$$

Figure 4-2 provides a graphical representation of the logic applied to derive the SN area carbon target.

Figure 4-2: SN Area Carbon Target Derivation



The resulting 2050 carbon target for the SN area was therefore found to be 0.55 $MtCO_{2eq}$ given that the per capita target was calculated as 1 tCO_{2eq} and the estimated population of the SN area in 2050 is 0.55 million. The 0.55 $MtCO_{2eq}$ figure was used to determine the success criteria of the scenarios modelled, as it provides a quantitative target to determine compliance of any given scenario for the SN area.

5.0 SCENARIO MAP

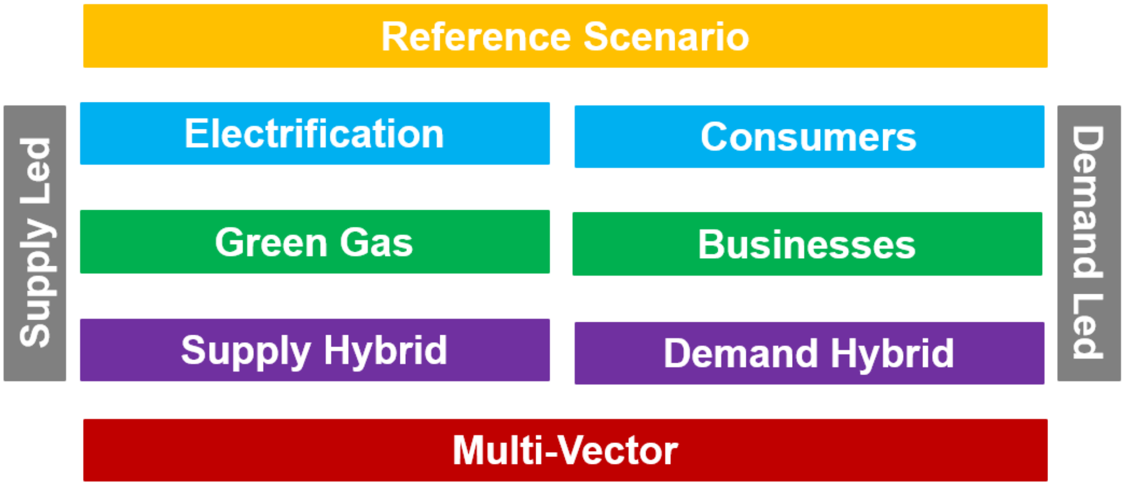
5.1 Modelling Approach

The purpose of the Green City Vision project is to understand the holistic implications of decarbonisation strategies to achieve a compliance in a particular region of interest. The modelling philosophy taken was to define a 2050 reference scenario for the SN area, based on the National Grid FES, from which a targeted decarbonisation strategy would be applied until compliance was achieved. Compliance is defined as a calculated emission of 0.55 $MtCO_{2eq}$.

The modelling philosophy used to derive the scenario map consisted of defining the technical boundary of compliance using single-vector solutions, and then incremental hybridisation of the single-vector scenarios, ultimately leading to a single multi-vector scenario.

The two broad decarbonisation approaches consisted of energy supply-driven scenarios and energy demand-driven scenarios. The supply-driven scenarios consisted of a low-carbon electricity scenario, a low-carbon gas scenario, and a hybrid scenario consolidating the two. The demand-driven scenarios consisted of a consumer-led scenario, a business-led scenario, and a hybrid scenario consolidating the two. Following consolidation of supply-driven and demand-driven approaches, a multi-vector scenario was developed to combine the two approaches and explore the opportunities that lie within this approach. A graphical representation of the scenario map is as follows:

Figure 5-1: Scenario Map



5.2 Scenario Definition

Each scenario was designed to explore the resultant system implications of applying different decarbonisation philosophies:

1) **Reference**: Baselining the likely 'status-quo' of the SN area in 2050, based on National Grid FES. Analysis and details in Section 6,

2) **Electrification**: Achieve compliance by solely leveraging low-carbon electricity production. Analysis and details in Section 7,
3) **Green Gas**: Achieving compliance by solely leveraging low-carbon gas production. Analysis and details in Section 8,
4) **Supply Hybrid**: Achieving compliance by balancing the deployment of low-carbon electricity and low-carbon gas, minimising disruptive impact where possible. Analysis and details in Section 9,
5) **Consumer-Led**: Achieving compliance by consumers taking full ownership via modifying behaviour and personal investment. Analysis and details in Section 10,
6) **Business-Led**: Achieving compliance by businesses taking full ownership via modifying behaviour and investment. Analysis and details in Section 11,
7) **Demand Hybrid**: Achieving compliance by balancing the modification of consumer and business behaviour as well as investment, minimising disruptive impact where possible. Analysis and details in Section 12,
8) **Multi-vector**: Achieving compliance by balancing supply-driven and demand-driven approaches, maximising low-regrets solutions and highlighting engineering trade-offs. Analysis and details in Section 13.

Figure 5-2: Conceptual Compliance Map

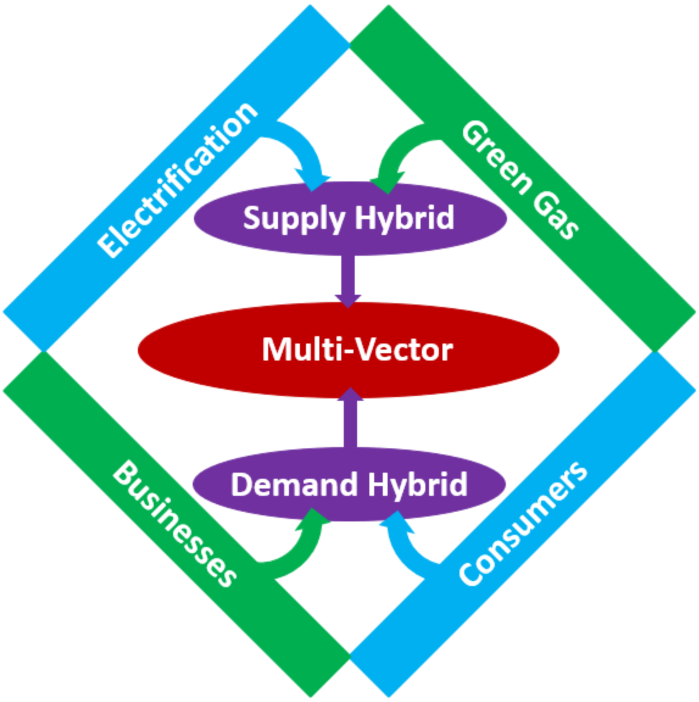


Figure 5-2 demonstrates a conceptual compliance map, with single vector solutions defining the boundary compliance solutions where optimum solutions lie within the map. Analysis of the system implications of each scenario was undertaken once each scenario achieved compliance. The advantage of the reference point scenario was in the fixed nature of the inputs due to them being specified. The modelling principals utilised for the subsequent scenarios to achieve compliance was to select fixed and variable parameters within a given decarbonisation to understand inherent engineering trade-offs.

6.0 REFERENCE SCENARIO

6.1 Modelling Principals

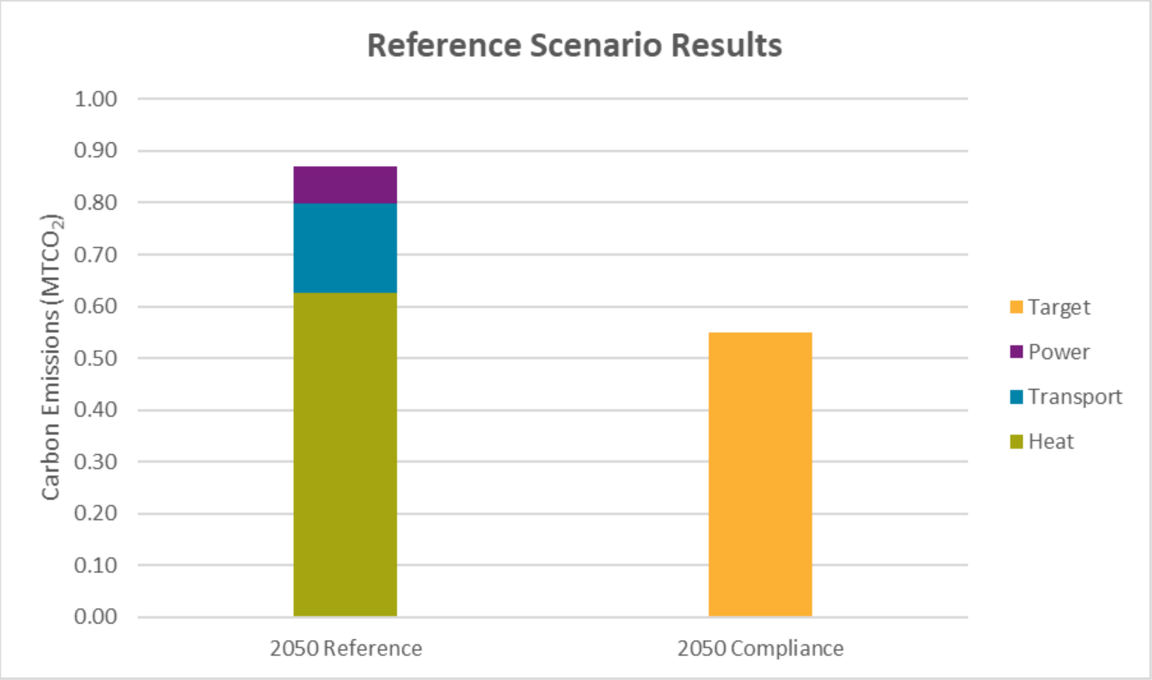
The reference scenario was utilised to define a likely 2050 starting point, from which a targeted decarbonisation strategy could be applied until compliance was achieved. For modelling expediency, the reference scenario was based on the Steady Progression scenario with National Grid FES. It should be noted that the Steady Progression figures, although deemed as the reference point, are still in themselves ambitious targets relative to the current energy landscape. This is discussed in Section 6.5.

The modelling principals applied primarily concerned the conversion from UK data to SN data. The primary conversion factors are described in Section 2.2 and the full breakdown of inputs used is given in Appendix 1.

6.2 SN Emissions

The overall emissions outcome of the reference point scenario aligns with National Grid conclusions of non-compliance. The calculated breakdown of SN emissions, from Pathfinder, are shown below and contrasted to the compliance target of 0.55 $MtCO_{2eq}$.

Figure 6-1: Reference Scenario Carbon Emissions



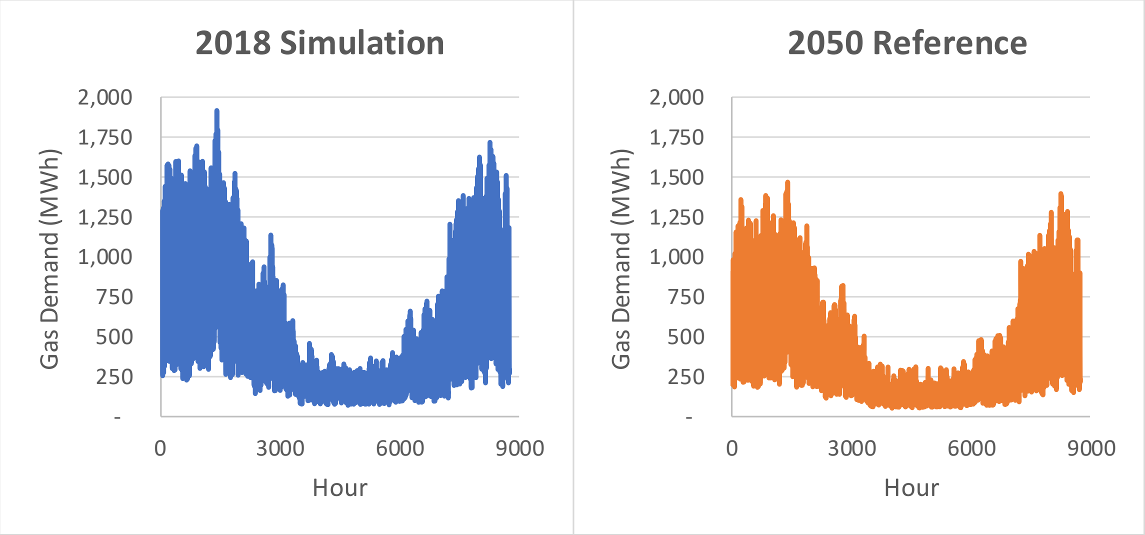
The calculated emissions from the reference point were 0.87 $MtCO_{2eq}$, therefore any decarbonisation strategy must reduce overall emissions by a further 0.32 $MtCO_{2eq}$ to achieve compliance – equivalent to a 37% reduction.

The profile of emissions is dominated by emissions relating to heat, given that these emissions alone are greater than the overall compliance target. This is a result of the assumptions inherent within the reference point relating to low-carbon gas deployment. The heat emissions reduction measures within the reference point account a for de minimis level of biomethane production, coupled with a low level of domestic electrification and an increase in home efficiency. The lack of significant change in fuel composition results in the near parity carbon intensity of heat, relative to today. Emissions associated with heating provision are shown as resulting, however this is due to an increase in home efficiency instead of a reduction in carbon intensity.

6.3 Impact on Gas Network

The implications for the gas network that feeds the SN area, which is owned and operated by WWU, are determined by the hour-by-hour demand profile of the end users. To understand the operational changes of the gas network that result from the development of the reference scenario, a comparison with today's gas network was carried out. The current operation of the gas network for the SN area, as profiled by Pathfinder, was created to compare to the reference scenario and allow consequences to be drawn regarding operational integrity. The below chart provides a comparison on the hour-by-hour demand profile of the SN area both in 2018 and in the 2050 reference point.

Figure 6-2: Gas Network Demand Profile Comparison



The profile of demand indicated the same general pattern of behaviour; however, with a reduction in each hour of a relatively constant proportion. The reason for the reduction in gas demand is due to:

1) Energy efficiency measures reducing the necessary gas supply for a given heating demand; and
2) A proportion of gas boilers either supported or fully replaced with heat pumps (HP).

The peak hour gas demand of the SN region in the reference scenario is around 1500 MWh, relative to around 2000 MWh in 2018. Therefore, the current capacity of the gas network would be capable of supplying the annual demand estimated within the reference scenario. The below table provides further data relevant to the operational strategy of the network which was generated by a comparison of the hourly demand data from Pathfinder.

Table 6-1: Gas Network Operational Metrics

Year	Average Hourly Demand (MWh)	Peak Hour Demand (MWh)	Utilisation (Av/Peak)	Maximum Rate of Demand Change (MW)	Average Diurnal Storage (MWh)	Average Diurnal Storage (% of daily demand)
2018	500	1,940	26%	570	1,720	14%
2050	380	1,480	26%	470	1,145	12%

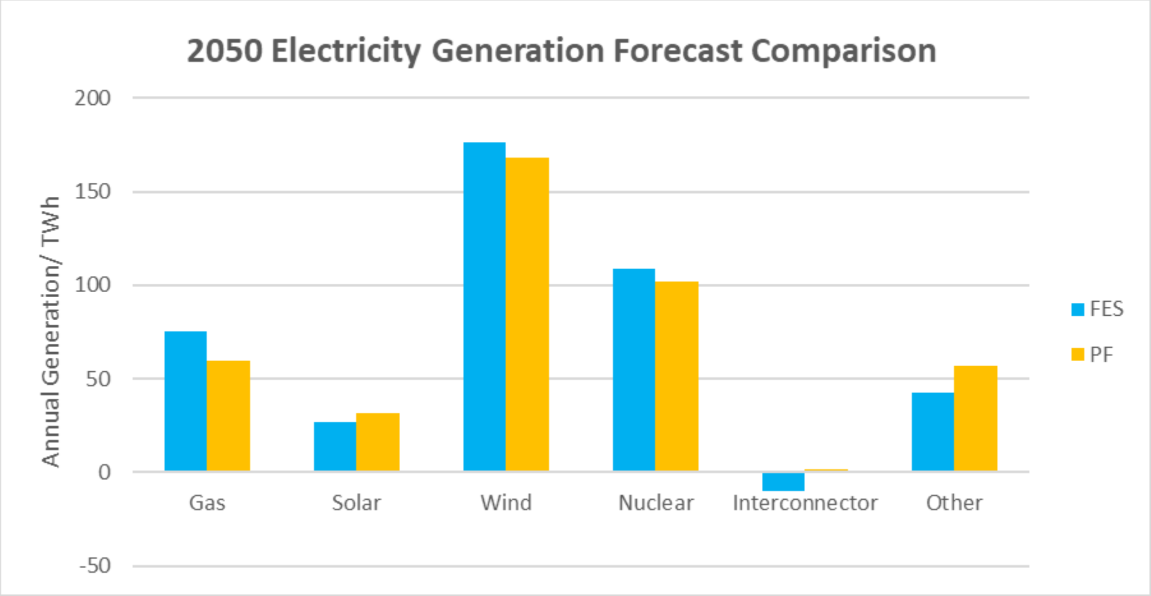
Table 6-1 indicates that the expected demand, utilisation and maximum rate of change are all within the current operating envelope of the network. Therefore, no significant investment would be expected in the gas network to accommodate the expected changes that would result from transitioning to the 2050 reference point, relative to current operation (beyond normal operational investment in the network to ensure safe and reliable operation). Diurnal storage requirements reduce on average, primarily due to an overall reduction in gas demand. The daily operational curve does vary much more though, gas demand is expected to be influenced to a greater extent by the availability of intermittent electricity generation assets.

6.4 Impact on Electricity Network

Gas network balancing within the reference point, which has in effect a single unlimited supply with one carbon intensity, is relatively straight forward - due to the lack of green gas deployment forecasted within the reference point. The balance of supply and demand within the electricity network is a more nuanced analysis due to the finite limit and varying carbon intensity of each generation source.

The ability of Pathfinder to replicate a known reference generation mix was first established, to confirm that any system insights could be relied upon. The 2050 reference point installed capacity mix was used to formulate the reference scenario, from which the Pathfinder logic selected generation using a merit order process based on availability and carbon intensity. The resulting 2050 national generation mix as calculated by Pathfinder, in comparison to forecasted figures within the National Grid FES workbook, is given below.

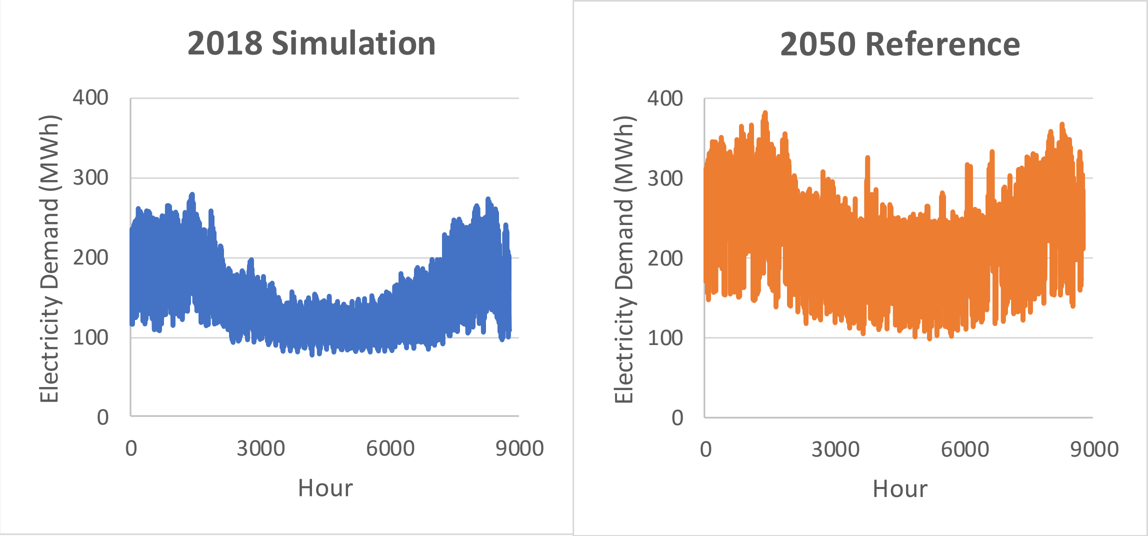
Figure 6-3: Electricity Generation Mix Forecast



Given the very close alignment between the Pathfinder output and FES figures, confidence can be ascribed to system insights and to further scenarios, as there is an alignment in calculation outputs. The resulting average carbon intensity of electricity was forecasted by Pathfinder to be 40 gCO_2/kWh, relative to the carbon intensity in 2017[2] of 265 gCO_2/kWh.

Following verification of the Pathfinder logic, a comparison of the 2050 reference scenario and the current electricity network was conducted to gain insight to the relative changes expected to precipitate as a result of transitioning from today to the 2050 reference point. The hourly breakdown of electricity demand within the SN area, both in 2018 and forecasted in 2050, is given below.

Figure 6-4: Electricity Demand Comparison



The hourly electricity demand profiles represent a significant shift in network operation. The total electricity demand in the SN area in 2018 was calculated to be 1.3 TWh, yielding an average demand of 148 MW, relative to a forecast 1.9 TWh demand in 2050, yield an average demand of 217 MW. This increase can be satisfied by the projected installed capacity mix, given that no blackouts resulted from the Pathfinder hourly analysis, however meaningful changes to the operation of the transmission and distribution network connecting the supply with demand were found. The Pathfinder model uses actual weather conditions over the course of a year and therefore provides a reasonable analysis for the actual weather conditions networks plan for. The below table provides an overview of these operational metrics.

Table 6-2: Electricity Network Operational Metrics

Scenario	Peak Demand Hour (MW)	Maximum Rate of Change (MW/h)
2018	280	55
2050	380	70
Change (%)	+36%	+28%

Given that both the peak demand and maximum rate of change of demand increase by approximately 30%, material network reinforcement within the SN area would be required to satisfy these operational requirements. It should be noted that these figures were generated with the assumption that 50% of EVs would not be charging during peak periods due to the availability of smart charging technology. An increase in peak demand of 36% by 2050 equates to a compound peak demand growth rate of 5% over each 5-year RIIO period until 2050.

The last operational metric of significant relevance is grid inertia, which was defined as the proportion of power generation with associated mechanical inertia. The importance of this system metric lies in the implications it has on grid frequency control. The aggregate momentum of rotating generators which feed electricity into the grid create, in effect, a shock absorber for events. When a large change in supply or is inflicted onto the electricity grid, this ‘shock absorber’ dampens the transient effect of that sudden change and allows the system as a whole to whether such real-world effects. There is a loose analogy with line pack limitations in the gas network – as the line pack range of a gas network reduces, the resilience of the network to sudden changes also reduces. The necessity for inertia in providing stable grid operation is recognised in National Grid ESO[21].

The projected installed capacity of generation sources from the current mix to the 2050 reference scenario represent a material change to low-carbon and intermittent sources, as shown in Figure 6-3. Intermittent sources such as solar PV and wind, although advantageous from a carbon perspective, reduce the capacity of the electricity grid to respond to sudden changes in the supply-demand balance. These implications have been recognised by National Grid and have led to the development of the Enhanced Frequency Control Capability (EFCC) project[5]. The table below outlines the forecasted changes to grid inertia which result from the electricity system projected in the reference scenario.

Table 6-3: Electricity Network Inertia

Scenario	Average Inertia (%)	Minimum-Hour Inertia (%)
2018	70	45
2050	40	20

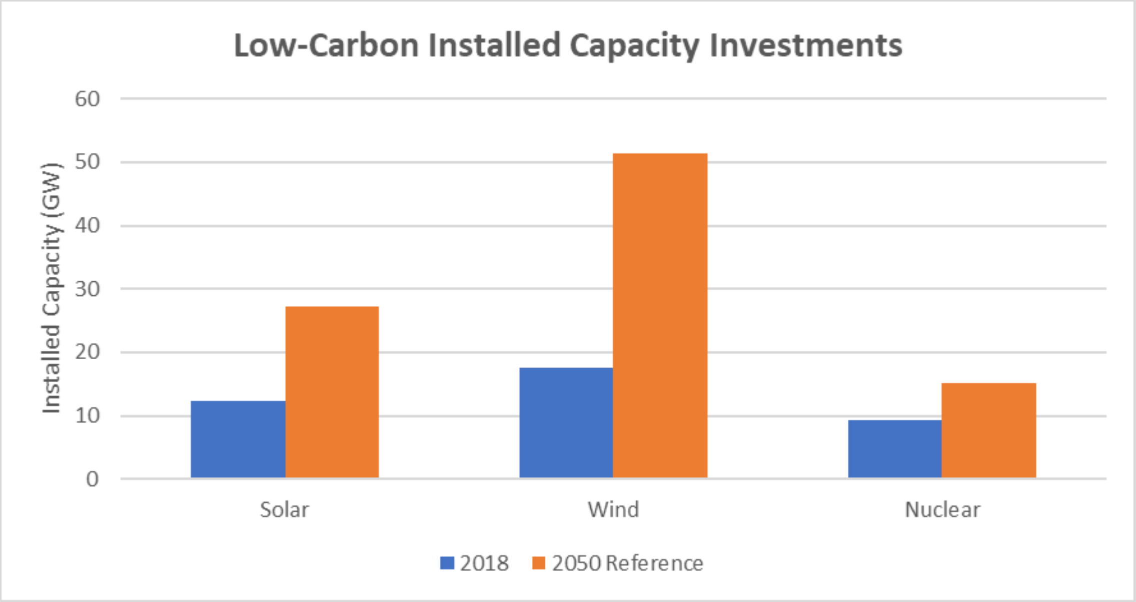
Both the average grid inertia and minimum-hour grid inertia are therefore forecasted to approximately halve between the current system and the 2050 reference scenario. National Grid ESO have recognised the need to develop the “Inertia/Grid Stability Market”[21] by Summer 2020 to ensure stable operation on the route to a zero-carbon electricity grid. The development of such services will be vital to enable a stable and reliable electricity grid as the penetration of low-carbon intermittent generation sources increases.

6.5 Investment Implications

The investment implications resulting from the reference scenario are minimal in relation to the gas grid, given the expected changes to operational requirements fall within the current operating envelope the network and little additional green gas deployment is included. However, ongoing operational investment in the network will be required to maintain safe and reliable operations.

The investment implications for the electricity grid are material, for both generation and transmission/distribution infrastructure. The installed capacity of low carbon generation sources, on a national scale, as forecasted by the reference scenario, is provided below.

Figure 6-5: UK Installed Capacity of Low Carbon Electricity Generation



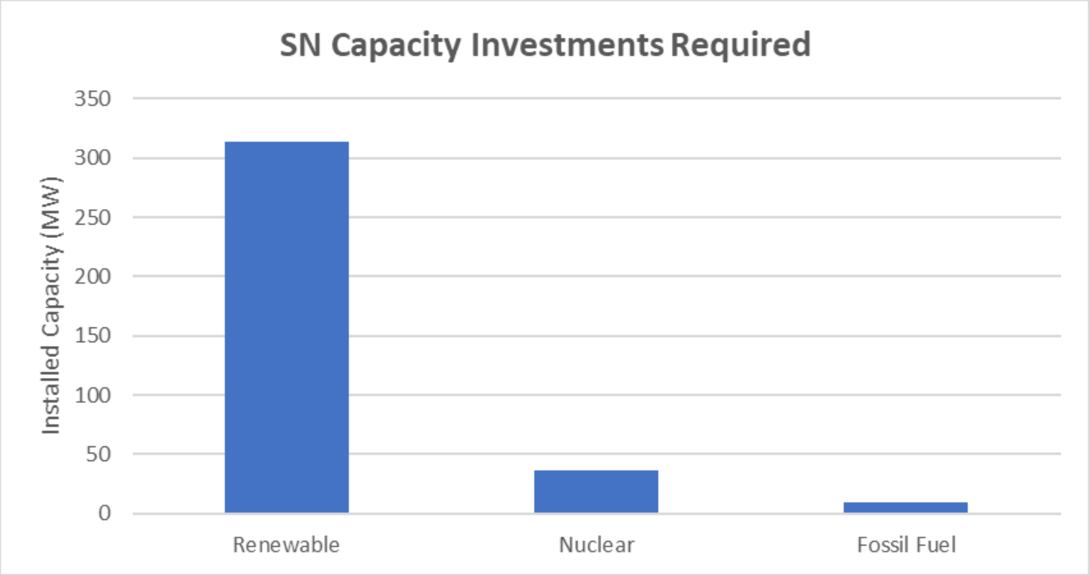
The relative increase for each generation source is approximately:

1) A doubling of solar capacity;
2) A tripling of wind capacity; and
3) A net 50% increase in nuclear capacity.

This level of investment in low carbon electricity generation, although technically feasible, would require large levels of commercial and regulatory support. Achieving the forecast nuclear generation capacity is likely to be particularly challenging, as according to FES Steady Progression nuclear capacity would reduce to 2.9 GW by 2030 and then increase to 15.2 GW in 2050. Which is an equivalent 2030+ build out rate of a Hinkley Point C every 5 year for 20 years.

By taking the difference between the current installed capacities and projected installed capacities, and then scaling to the SN area, a target of low-carbon generation investment can be derived. This figure would serve to act as a local 'fair share' of additional capacity to achieve the national generation mix. The scaling of the installed capacity differences accounted for changes in population, demographics, energy efficiency measures and technology deployment such as EVs. The analysis yielded the following profile of necessary local capacity investments:

Figure 6-6: SN Capacity Investments Required



The above investment targets, if materialised, would result in the SN area providing the necessary level of 'fair share' capacity to achieve the reference point scenario of the Steady Progression FES scenario. Given the magnitude of calculated nuclear capacity, a practical aggregation of the above data could result in the following investment targets:

- Installation of 350 MW of low-carbon electricity capacity; and
- Installation of a small (10-20 MW) flexible turbine.

Swindon Borough Council's current target for low-carbon electricity capacity by 2020 is 200 MW. The largest operational low-carbon generation site is the 60 MW Swindon Solar Park, therefore around 140 MW of additional operational low-carbon capacity would be required to achieve the 2020 target. Assuming the current target is achieved, to push further and achieve the 2050 reference point target of 350 MW, an additional 210 MW of low-carbon capacity would need to be construction between 2020 and 2050.

The required investment within the electricity network would likely extend to the network itself, given the:

1) ~30% increase in estimated peak hour demand;
2) ~30% increase in maximum rate of change in demand; and
3) ~50% reduction in grid inertia.

These operational changes would require a thorough review of the network configuration supporting the SN area, as well as frequency control equipment, to ensure a resilient and capable network is guaranteed in 2050.

6.6 Energy Efficiency Sensitivity

The reference point utilises FES data[6] with regards to average home EPC rating progression to determine the expected gains in energy efficiency. The figure used within the reference point is a 19% increase in home efficiency, corresponding to an average increase from Band D EPC to Band C EPC.

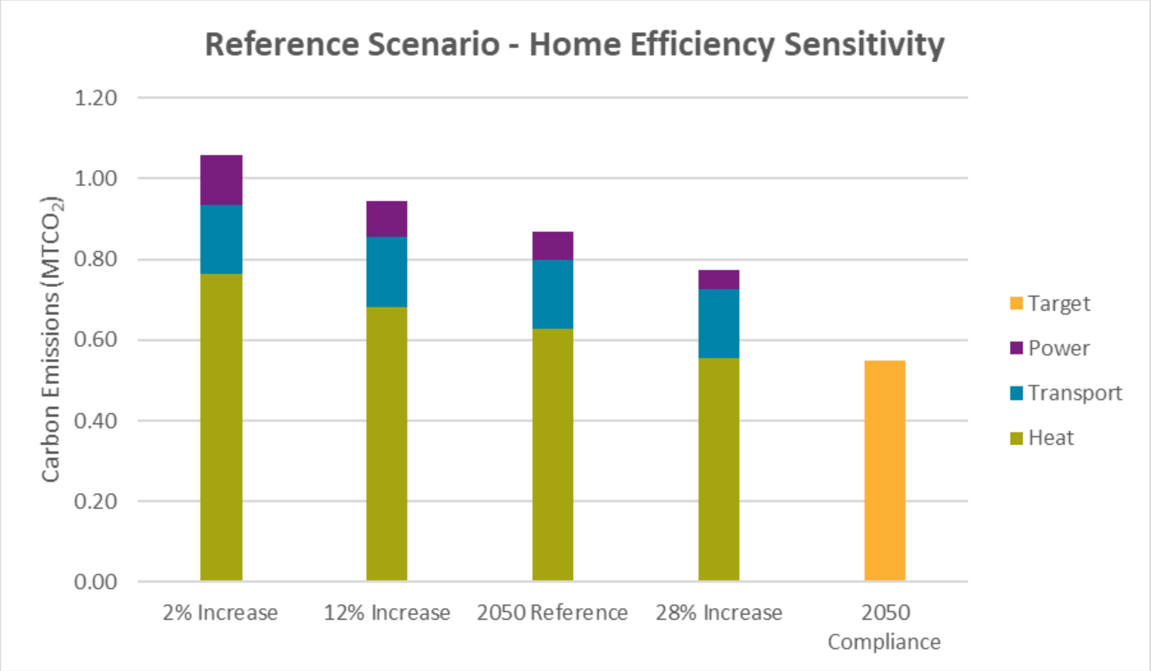
Due to the sensitivity of the outturn emissions profile, the energy efficiency figure has been explored in more detail to understand the aggregate effects of different increases in energy efficiency. The table below provides a breakdown of energy efficiency progression based on potential decisions made by consumers or policy makers[7].

Table 6-4: Energy Efficiency Sensitivities

Energy Efficiency Gains (%)	Sensitivity
2	Regulated change based on current policy
12	Cost effective to consumer but not currently policy driven
19 (2050 reference)	Cost effective to society but not currently policy driven
28	Technical upper limit

The impact of energy efficiency measures affects both electricity and heat use, given the breadth of available technologies such as LED lightbulbs and cavity wall insulation. The current functionality within Pathfinder reduces each hour of demand by a constant percentage, as specified by the user. In reality, however, the extent of any energy efficiency measure would be variable throughout the year. For example, the installation of rooftop PV would qualify as an energy efficiency measure, but if not coupled to an air-source heat pump (ASHP), it would not reduce peak winter gas demand. The resultant emissions profile for each energy efficiency sensitivity, as shown in Table 6-4.

Figure 6-7: Energy Efficiency Emissions Sensitivity



The emissions profiles in Figure 6-7 provide insight into the potential emissions reductions that could be achieved through appropriate investment and policy decisions. However, the profiles also serve to demonstrate the limitations of energy efficiency measurements, as the technical limit profile (28% gains) still yields a non-compliant scenario.

6.7 Electric Vehicle Uptake Sensitivity

The projections of electric vehicle uptake within FES show a 90% adoption across cars and vans by 2050 and a 20% adoption of Compressed Natural Gas (CNG) Heavy Goods Vehicles (HGVs). When viewed from the perspective of current transport policy and average vehicle lifetimes, these figures do not seem unreasonable. The two drivers being:

1) The mandated elimination of new cars sales by 2040 which are purely internal combustion engines; and
2) The average lifetime of a personal vehicle being 10 years.

A third driver for the adoption of EVs is the introduction of clean air zones, predominantly within cities, to reduce ground level pollution. Although less quantifiable in their direct effect, the introduction of clean air zones via a levy on internal combustion engines provides a further economic incentive to promote the adoption of EVs.

The above rationale does not take account of wider barriers to deployment, such as charging infrastructure investment. There is also an inherent assumption that vehicle manufacturers will be capable of producing electric vehicles at the rate required to facilitate this adoption rate, which equates to over 1 million electric vehicles sold in the UK per year. To take account of the potential implications that the above barriers could inflict on the adoption of EVs, and the resulting effect on the emissions profile of the SN area, a number of sensitivities were reviewed. The table below provides a description of the sensitivities chosen.

Table 6-5: EV Adoption Sensitivities

EV Adoption	Sensitivity
90% (2050 reference)	2050 FES projection
70%	EA Technology assessment for SSEN[8]
50%	Double the delta between the above two

The outturn emissions implications for each sensitivity is a balance between road transport and electricity emissions. As the rate of EV adoption increases the emissions associated with road transport reduce, however the emissions associated with electricity production increase. This effect is due to the increase in peak electricity demand that results from charging behaviour. The Pathfinder model uses a merit order process to select the lowest carbon generation source available. However, it is inevitable that the carbon intensity of electricity is greater at peak than the average carbon intensity across the year. The Pathfinder model aggregates hour by hour carbon intensity to give total annual emissions, rather than simply applying the average. It therefore follows that the emissions profile for a given area is sensitive to the proportion of vehicles charging at peak, and what implications this has for the carbon intensity of generation. The aggregate effect on the emissions profile of the reference point, resulting from each sensitivity described within Table 6-5, is shown below.

Figure 6-8: EV Adoption Emissions Sensitivity

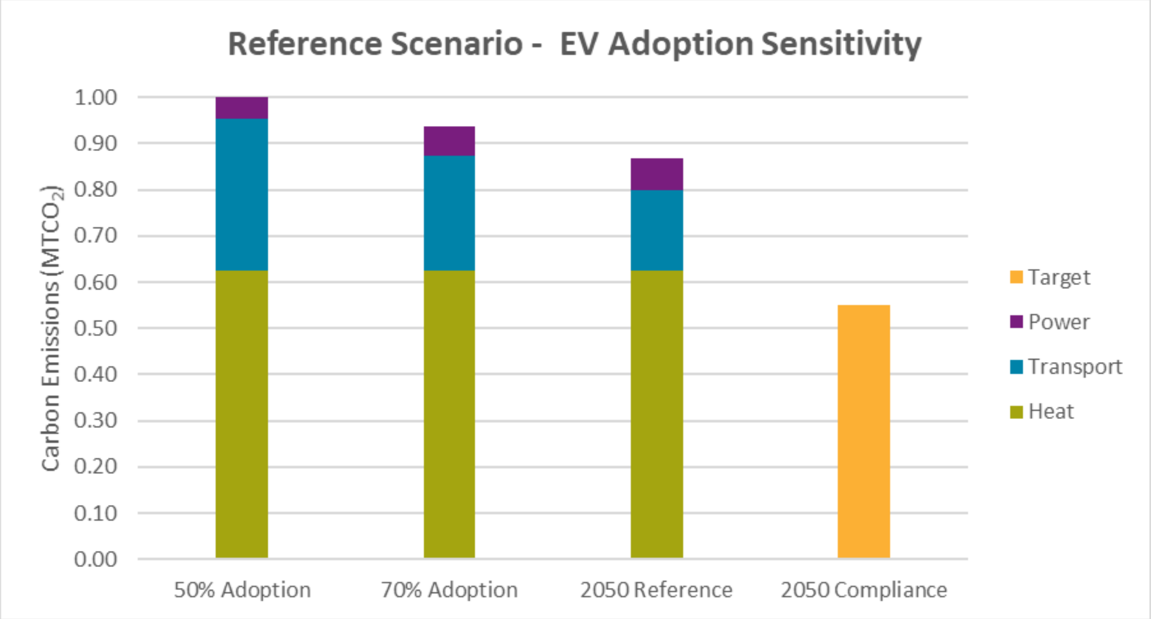


Figure 6-8 illustrates that the effect of EV adoption is of a similar magnitude to energy efficiency, and serves to quantify the carbon emissions effects of not achieving the 90% adoption rate assumed by National Grid.

7.0 ELECTRIFICATION SCENARIO

7.1 Modelling Approach

The electrification scenario explored whether compliance could be achieved using low-carbon electricity alone. This constitutes a single-vector supply strategy and defines one of the corners of a conceptual compliance map, Figure 5-2. The reference scenario forecasts decarbonisation gains primarily through the electrification of transport and the construction of low-carbon generation to provide the necessary electricity to the EVs. Therefore, to achieve compliance, any further gains would have to be achieved through the electrification of heat – principally through the installation of heat pumps as replacements or supporting heat sources to domestic gas boilers.

As discussed in Section 5.2 the methodology used to achieve compliance consisted of fixing parameters which were deemed to be sensible engineering changes within a given decarbonisation strategy, followed by varying other parameters until compliance was achieved. The fixed parameters within the electrification scenario consisted of:

1) Increasing electrification of cars and vans from 90% to 100%; and
2) Doubling the electrification of ICE HGVs/Buses.

The variable parameters within the electrification scenario consisted of:

1) Installing ASHPs at the forecasted ratio between replacements and hybrid systems within the reference point, whilst increasing low-carbon capacity to ensure enough electricity was available on an hourly basis to match demand; and
2) The installation of ASHPs and resulting need for more low-carbon capacity were increased until compliance was achieved.

The resultant implications for consumers, the gas network and electricity network, along with investment implications, are discussed below.

7.2 Impact on Consumers

The impact for consumers within the electrification scenario primarily consists of the cost and disruption of installing ASHPs, either as replacements to their gas boilers or as supporting heat sources as a hybrid system (H-ASHP). The domestic profile of heating sources necessary to achieve compliance within the SN area, in comparison to the current profile, is given below.

Table 7-1: Electrification Compliant Domestic Heating

Heating Source	2018 (k)	2050 Electrification (k)
Gas Boiler	160	95
Gas Boiler + ASHP	0	40
ASHP	0	60
Other	40	40

The off-grid housing and purely electric heating were assumed to remain unchanged, hence a constant 40,000 'other' heating source. The summary implications for consumers, which results from the necessary changes required to achieve compliance are:

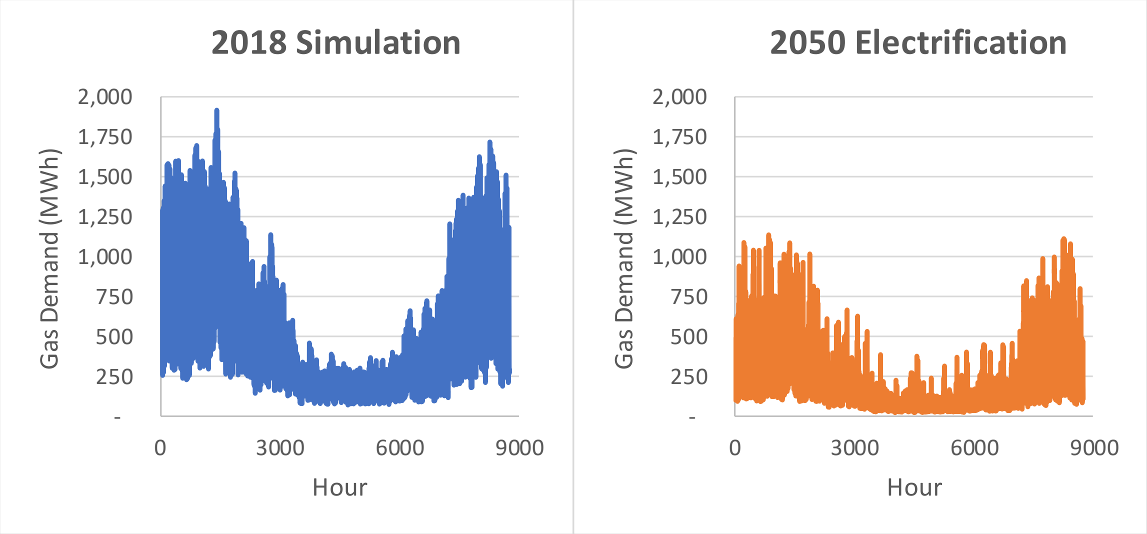
1) Replacing 60,000 gas boilers with ASHPs; and
2) Installing 40,000 ASHPs as hybrid systems.

The resulting cost and disruption to consumers would vary depending on the change required, given that the installation of a hybrid system is cheaper and less disruptive than replacement with an ASHP. This is because it doesn't require larger heat emitters or underfloor heating due to availability of higher quality heat. BEIS estimate these reduced interventions result in a 25% reduction installation cost of a hybrid ASHP system relative to a full ASHP[11]. However, full replacement ASHPs yields a greater system carbon saving due to the nature of calculation methodology utilised within the Pathfinder model.

7.3 Impact on Gas Network

Given that this scenario focused on the resulting implications of achieving compliance via a single-vector supply-driven strategy of low-carbon electricity, the outturn effects for the gas network were found to reduce the annual and peak demand for gas. The effect of employing an electrification scenario to achieve compliance within the SN area, would create the following operational profile of the gas network in 2050 compared with 2018.

Figure 7-1: Gas Demand Comparison (SN Area): Electrification Scenario



The use of gas within the SN area would dramatically reduce within a compliant scenario based on electrification. The below table outlines the key changes that would be expected within a compliant electrification scenario.

Table 7-2: Change in Gas Demand (SN Area): Electrification Scenario

Operational Parameter	2018	2050 (Electrification)	Change (%)
Average Demand (MW)	500	240	- 50%
Peak Hour Demand (MW)	1,920	1,140	- 40%
Peak rate of change (MW/h)	560	440	- 20%
Average Diurnal Storage (MWh)	1,720	680	- 60%
Average Diurnal Storage (% of daily use)	14%	12%	- 2%

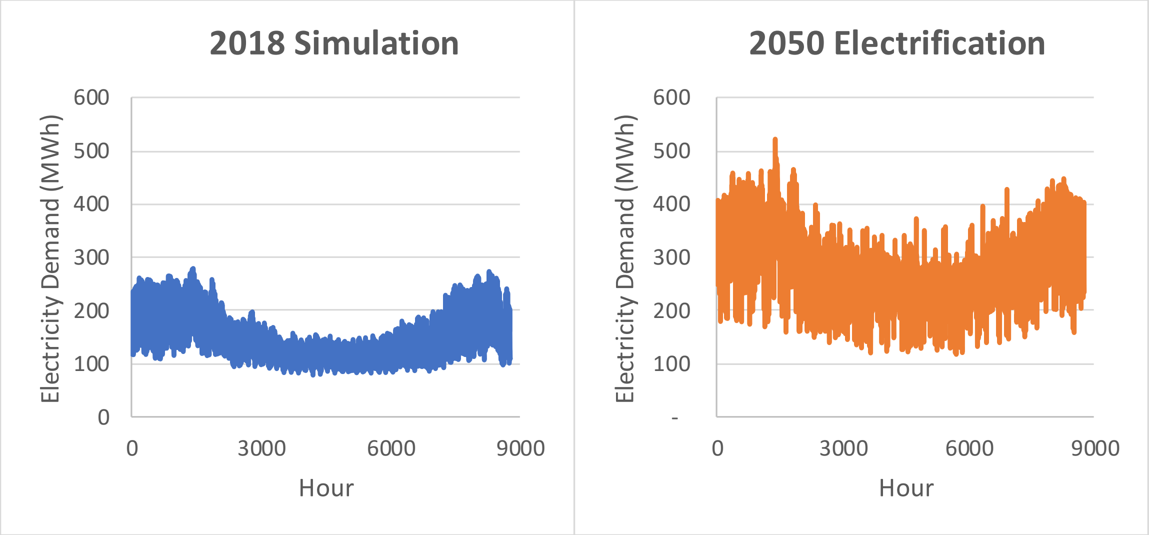
A reduction in annual demand of 50% represents a significant change to the operation of the gas network. If 2050 compliance (80% reduction relative to 1990) is to be achieved through electrification of transport and heat, a precedent would have been established which could further reduce gas usage within context of a net-zero carbon target.

The daily gas demand patterns produced by Pathfinder indicated a much more variable daily pattern. This was due an increased influence of charging vehicles on flexible generation. In some days in the summer, where heating demand during the day was minimal and a calm night resulted in low wind generation, the overnight demand for gas was greater than the daytime demand for gas – as flexible gas generation was required to charge constrained electric vehicles overnight. Therefore, to ensure accurate gas demand forecasting, greater visibility of the forecasted electricity generation mix would be required.

7.4 Impact on Electricity Network

To achieve compliance through electrification, the resultant implications for the operation of the electricity grid and supply of electricity would be profound. Based on the Pathfinder output of electricity demand, it is likely that a significant programme of investment would be required to ensure the network was capable delivering peak supply and handing the forecasted rate of change. The hourly operation of the electricity grid supplying the SN area with the required level of low-carbon electricity to achieve compliance, in comparison to the current (2018) operation, is shown below.

Figure 7-2: Electricity Demand Comparison (SN Area): Electrification Scenario



The key operational changes that would result from achieving compliance through electrification are summarised below.

Table 7-3: Change in Electricity Demand (SN Area): Electrification Scenario

Operational Parameter	2018	2050 (Electrification)	Change (%)
Average Demand (MW)	150	300	+ 100%
Peak-hour Demand (MW)	280	520	+ 90%
Peak rate of change (MW/h)	55	150	+ 170%
Annual Inertia	70%	45%	- 35%
Minimum-Hour Inertia	45%	20%	- 55%

The output of the Pathfinder model indicated an increase in peak demand of 90%. Given that forecast peak demand is the principal operational parameter for a network design, it is very likely that substantial reinforcement would be required to accommodate this increase. The exact nature of any reinforcement programme would be influenced by local utilisation and geographical distribution of additional demand. Within the Electrification scenario set up, smart solutions were optimised to enhance utilisation of the electricity network. An example of a smart solution was the split between constrained and unconstrained EV charging patterns, where the split was optimised to minimise peak demand. Therefore, the figures presented in Table 7-3 are minimal values of forecasted change, and it would be contingent upon the deployment of smart solutions.

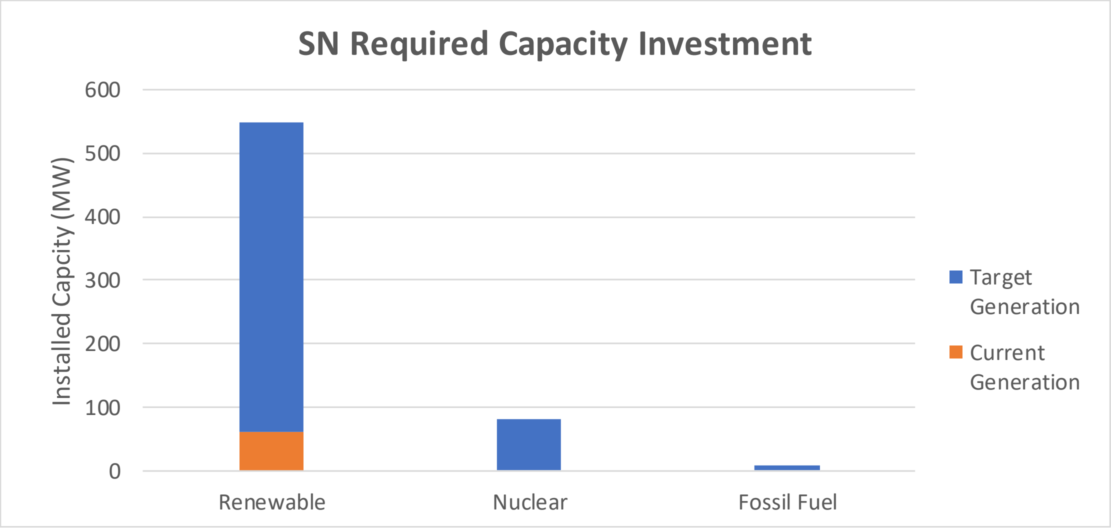
Electrifying transport to the extent forecasted, along with an electrification of heat, is forecast to triple the peak rate of change of demand, based on the Pathfinder output. The effect of an increasingly dynamic network would need to be reviewed due to any implications resulting from maximum ramp rates of network assets.

The electrification of heat through the application of heat pumps, either as hybrids or replacement systems, was one of the key drivers of the outturn scenario operational envelope. The application of heat pumps to decarbonise heat will likely to be contingent on a number of local characteristics, such as; the suitability of housing stock to accept heat pumps; and, the availability of low-carbon electricity. Regions with currently constrained low-carbon generation would be more suitable than those without, and regions with more efficient homes would be more suitable than those with older homes – as a result of increased leakage from older housing stock.

7.5 Investment Implications

Alongside the application of smart solutions to a substantial reinforcement programme, a significant programme of low-carbon installed generation capacity would need to be delivered. To supply the necessary level of electricity to satisfy the demands within the SN area, the following investment profile of low-carbon installed capacity would be required.

Figure 7-3: Required Investment in Electricity Generation (SN Area): Electrification Scenario



The above investment profile, if materialised, would represent the ‘fair share’ of capacity investments from the SN area to achieve compliance through the single-vector supply-driven strategy of electrification. The largest current operational low-carbon generation site in the SN area is the 60 MW Swindon Solar Park. To achieve the level of ‘fair share’ low-carbon capacity within Figure 18, the equivalent of a Swindon Solar Park would need to be constructed every 3 years from now until 2050.

To understand the total level of investment required to achieve compliance of the SN area through an electrification strategy, it is helpful to breakdown the necessary changes into 5-year increments to calibrate expectations on the magnitude of the challenge. A time interval of 5-years has been chosen as this is the time interval of the RIIO-2 price control period. Applying this approach results in the following investment targets that must be achieved every 5-years until 2050:

1) Construction of around 100 MW of low-carbon capacity (based on Figure 7-3);
2) Installation of 16,000 ASHPs (based on Table 7-1);
3) Purchasing of 44,000 electric vehicles (based on 100% EV adoption by 2050); and,
4) Investment to accommodate a compound growth in peak demand of 11% (based on Table 7-3).

Investment on this scale would be very ambitious as it would require a highly engaged and financially able public to purchase the ASHPs and EVs, along with proactive and focused regulatory bodies (both local and national) and a ready supply of low-carbon capacity projects with financial backing.

8.0 GREEN GAS SCENARIO

8.1 Modelling Approach

The Green Gas scenario explored whether compliance could be achieved through the use of low-carbon gas. This scenario was the second single-vector supply-driven scenario and forms another boundary of the conceptual compliance map, Figure 5-2. The reference point scenario assumes virtually no additional deployment of green gas by 2050, either via biomethane or hydrogen.

To achieve compliance through the deployment of green gas, there are two broad options available – biomethane and hydrogen. Biomethane is chemically comparable to natural gas and can be generated using domestic feedstock, therefore it is an attractive option for low-carbon gas production. The limitation for biomethane capacity is the availability of sustainable feedstock. Hydrogen production at scale would be contingent on Carbon Capture, Utilisation and Storage (CCUS) infrastructure and it is chemically distinct from natural gas, however it is not feedstock limited. The deployment of biomethane and hydrogen is therefore non-competitive, with each technology offering advantages to compliment the other.

Given the feedstock availability limitation of biomethane, two green gas options were considered in the Green Gas scenario:

1) **Biomethane supported by hydrogen blending**: Compliance through deployment of biomethane alongside a $20\%_{vol}$ blend of hydrogen for domestic and commercial consumers and conversion of industrial users; and,
2) **Hydrogen conversion**: Full conversion of the LTS and the creation of a hydrogen city.

Option one would likely be less disruptive to consumers as there would be no requirement to convert gas appliances, however it would be dependent on biomethane imports (either as feedstock or finished gas). Option two would be more disruptive to consumers, however would offer a greater ultimate decarbonisation potential.

8.2 Impact on Consumers

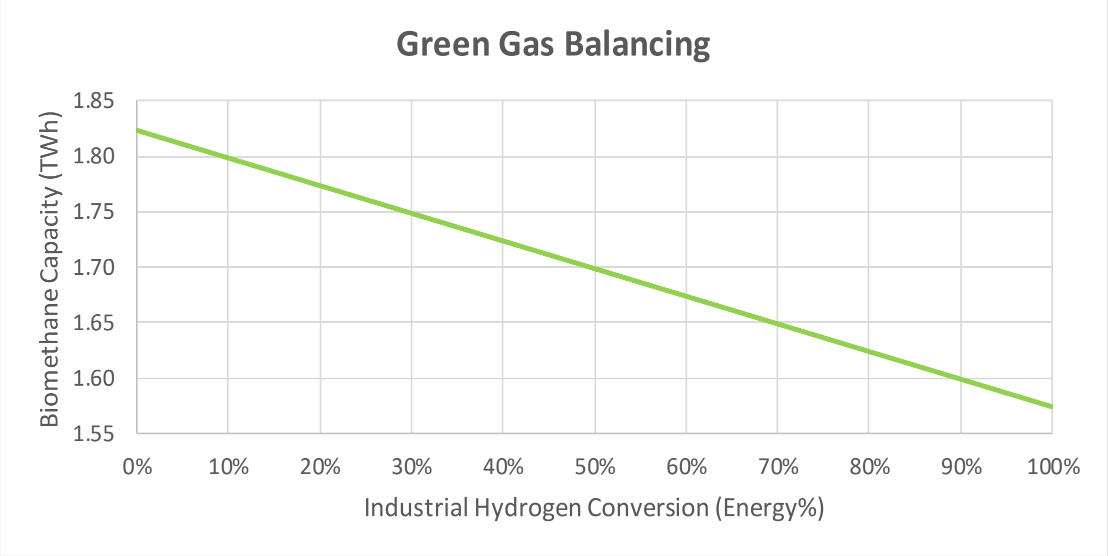
The resultant implication for consumers is principally a function of the assumed role that hydrogen takes in the green gas balance. Where hydrogen blending supports biomethane deployment to achieve compliance, no change is required for consumers. This is because the nature of gas would be change to the extent that requires modify or change appliances. In the conversion vision, all appliances would require replacement with purposely designed hydrogen boilers. Therefore, within this option approximately 230,000 households within the SN area would require intervention.

8.3 Impact on Gas Network

8.3.1 Biomethane Supported by Hydrogen Blending

The implications for the gas network from this strategy results from a balance between biomethane and hydrogen. To understand the balance between the two technologies, biomethane deployment was varied to achieve compliance as industrial conversion to hydrogen was varied between 0 - 100% alongside a constant 20 vol% blend for domestic and commercial consumers. The resulting balance between biomethane and hydrogen for the SN area, as calculated by the Pathfinder model, is shown below.

Figure 8-1: SN Biomethane and Industrial Conversion: Green Gas Compliance



The required level of biomethane capacity to achieve compliance reduces as the proportion of industrial gas use is converted to hydrogen. The SN area has a smaller industrial base than the UK average, as only 10% of gas capacity is associated with industrial usage. Therefore, the required level of biomethane capacity to achieve compliance is greater per capita than the UK average.

The indicative limit of biomethane capacity resulting from domestic feedstock is 100 TWh[9]. Using this figure, the natural ‘fair share’ allocation to the SN area in 2050 based on gas usage would be 0.6 TWh. Therefore, if the SN industrial cluster was completely converted to hydrogen, the resulting biomethane capacity required to achieve compliance would still be 2.5 times the natural allocation. If this strategy was replicated in locations with a larger industrial base, such as Merseyside or South Wales, the proportion of biomethane capacity required would be significantly lower due to the greater decarbonising effect of industrial conversion. Additional biomethane beyond the natural SN allocation could conceivably be supplied via two routes:

1) Domestic biomethane reallocated other compliant regions; and,
2) Importing feedstock or biomethane.

The exact balance between the deployment of biomethane and conversion of industrial clusters within this strategy would be predicated on the development of the wider UK and international energy markets and the deployment strategy of CCUS within the UK. The utilisation of a national hydrogen transmission system would allow hydrogen production and CCUS infrastructure to be located in strategic locations along the coastline of the UK and allow inland areas such as the SN area to benefit. Local embedded biomethane capacity could be developed within the SN region to allow the balancing of technologies to create ensure a compliant region. Feedstock arrangements would be required to ensure sufficient local biomethane capacity could be deployed.

8.3.2 Hydrogen Conversion

The implications for the SN gas network within a hydrogen conversion deployment strategy would be to remove the need for biomethane deployment. This is due to compliance being achieved through the resulting carbon reductions of converting all gas users to hydrogen. Biomethane capacity could be reallocated to other regions within the UK that are more remote than the SN region, and therefore would likely have a greater focus on local solutions for decarbonisation.

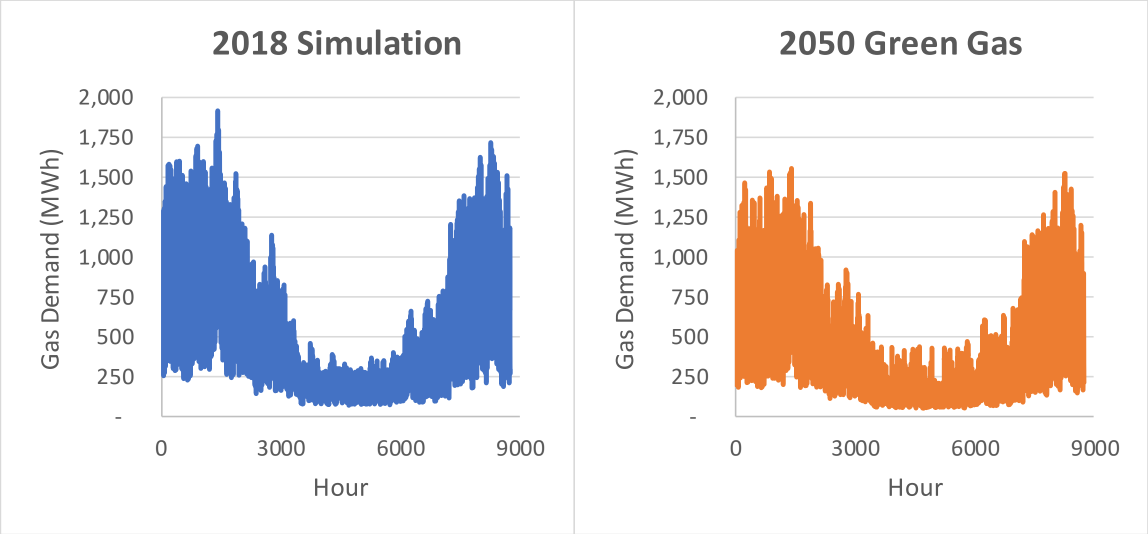
The implications for the gas network would be significant within this option. Beyond the consumer implications described in Section 8.2, investment in both the Local Transmission System (LTS) and National Transmission System (NTS) would be required to ensure they were ready for hydrogen conversion.

Much like the option of biomethane supported by hydrogen blending, any hydrogen infrastructure servicing the SN area would need to be a part of a wider infrastructural programme. Therefore, both options would be contingent on national policy and regulatory direction.

8.3.3 Modelling Results

The overall energy requirements are constant for both of the outlined green gas option. The reason being that compliance, within a green gas scenario, would be contingent on achieving a given carbon intensity of gas. Therefore, the comparison of options provides insight into how this carbon intensity could be achieved, but does not change the macro demands for energy. The hourly breakdown of total gas demand in both visions is shown below.

Figure 8-2: Gas Demand Comparison (SN Area): Low Carbon Gas Scenario



The reason for the lower overall gas demand in the Green Gas scenario is due to the increase in home energy efficiency that results in a lower gas demand for a given heating demand. The overall expected changes to gas demand in the SN area, if compliance is to be achieved through green gas deployment, are shown below.

Table 8-1: Change in Gas Demand (SN Area): Low Carbon Gas Scenario

Operational Parameter	2018	2050 (Green Gas)	Change (%)
Average Demand (MW)	500	410	- 18%
Peak-hour Demand (MW)	1,920	1,560	- 19%
Peak rate of Change (MW/h)	560	490	- 13%
Average Diurnal Storage (MWh)	1,720	1,140	- 35%
Average Diurnal Storage (% of daily use)	14%	11%	- 3%

The output of the Pathfinder model indicate that the peak and annual gas demands within a compliant SN area via green gas deployment are within the current operational demands of the gas network. The calculated diurnal storage requirements reduce as a result of lower overall gas demand, and the same increase in daily use variability as the Electrification scenario was found – that is, potentially having more gas demand overnight than in the day during summer period with calm winds overnight and a need to charge constrained electric vehicles.

The calorific value of hydrogen by volume is 32% of the calorific value of methane[10]. Industrial usage of hydrogen for both options would likely be supplied by a bespoke hydrogen transmission system, therefore storage requirements for the LTS would principally be related to the relative caloric value of the gas it distributes. The main source of current gas storage takes the form of linepack, which is gas stored within the network itself – ready to be let down as demand increases. The below table outlines the forecasted implications for inter-seasonal storage requirements within the SN region for the LTS based on achieving compliance via biomethane supported by hydrogen blending or hydrogen conversion.

Table 8-2: 2050 LTS Inter-Seasonal Storage Requirements

Calculation Parameter	Biomethane + Hydrogen Blend	Hydrogen Conversion
LTS Hydrogen Proportion (vol%)	20	100
LTS Methane/Biomethane Proportion (vol%)	80	0
Relative Calorific Value (energy/volume)	86%	32%
Relative Energy Demand (2050/2018)	82%	82%
Relative Volume Requirement (2050/2018)	95%	260%
Additional Inter-Seasonal LTS Storage	-	160%

The additional inter-seasonal storage requirements required for hydrogen conversion could be achieved via greater utilisation of existing network assets i.e. greater utilisation of the existing pressure envelope, or through the construction of dedicated storage facilities such as salt caverns.

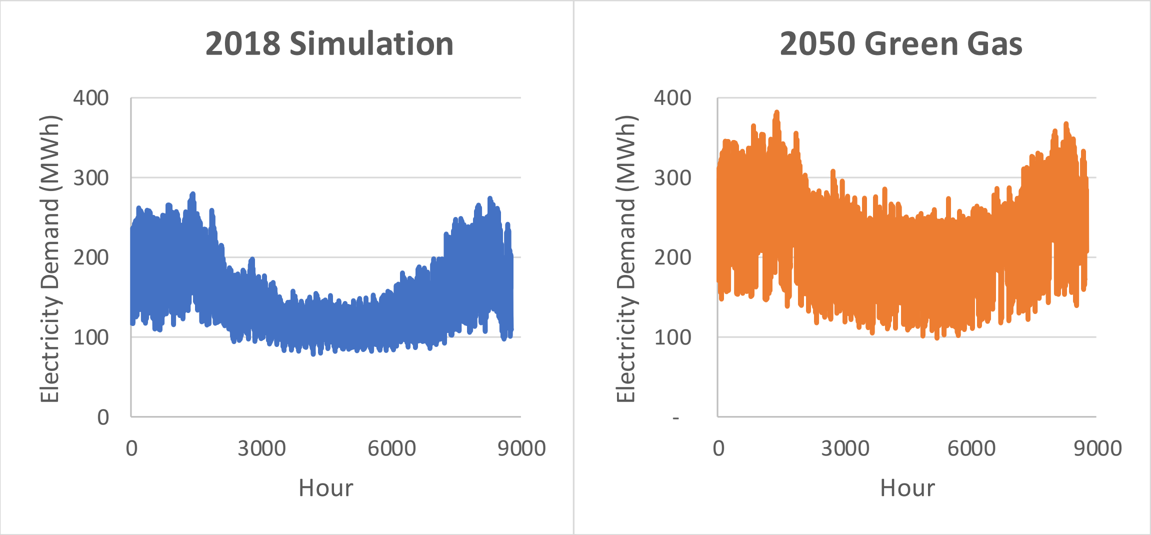
Based on the output of the Pathfinder modelling, there would be no clear need for investment in additional storage to facilitate the biomethane plus blending option as the reduction in demand counterbalances the reduction in calorific value of the gas. However, greater utilisation of the gas network pressure envelope would greatly promote the deployment of the necessary biomethane capacity. By providing greater operational functionality in the form of compressing gas back up the LTS pressure tiers, biomethane production could be maintained during periods of low demand for utilisation during periods of high demand. This potential storage mechanism is being reviewed by the WWU OptiNet project[31], and if successful will be an enabling innovation to promote biomethane deployment.

The overall magnitude of change required in the gas network, much like consumers, would be a function of the chosen green gas option. Delivering compliance through biomethane supported by a hydrogen blend would likely require less investment in gas network assets, however it would be contingent on securing sufficient quantities of sustainable biomethane feedstock. Whereas delivering compliance through hydrogen conversion would require more gas network investment, principally to accommodate the lower calorific value, but would allow domestic biomethane feedstock to be reallocated to other regions within the UK.

8.4 Impact on Electricity Network

As the Green Gas scenario achieved compliance via reducing the carbon intensity of gas, the incremental change to the electricity network relative to the reference point was found to be very low. As the changes made within the scenario modelling were additive to the reference point to ensure compliance was achieved, the electricity network in 2050 would still be impacted by the electrification of transport forecasted in the reference point. The hourly demand on the SN electricity network within the Green Gas scenario is shown below.

Figure 8-3: Electricity Demand Comparison (SN Area): Low Carbon Gas Scenario



The overall electricity demands and volatility are still forecasted to increase, due to the effect of EV charging requirements on the electricity network. The overall operational changes that would need to be accommodated are summarised below.

Table 8-3: Change in Electricity Demand (SN Area): Low Carbon Gas Scenario

Operational Parameter	2018	2050 (Green Gas)	Change (%)
Average Demand (MW)	150	220	+ 45%
Peak-hour Demand (MW)	280	380	+ 35%
Peak rate of change (MW/h)	55	70	+ 25%
Annual Inertia	70%	50%	- 30%
Minimum-Hour Inertia	45%	20%	- 55%

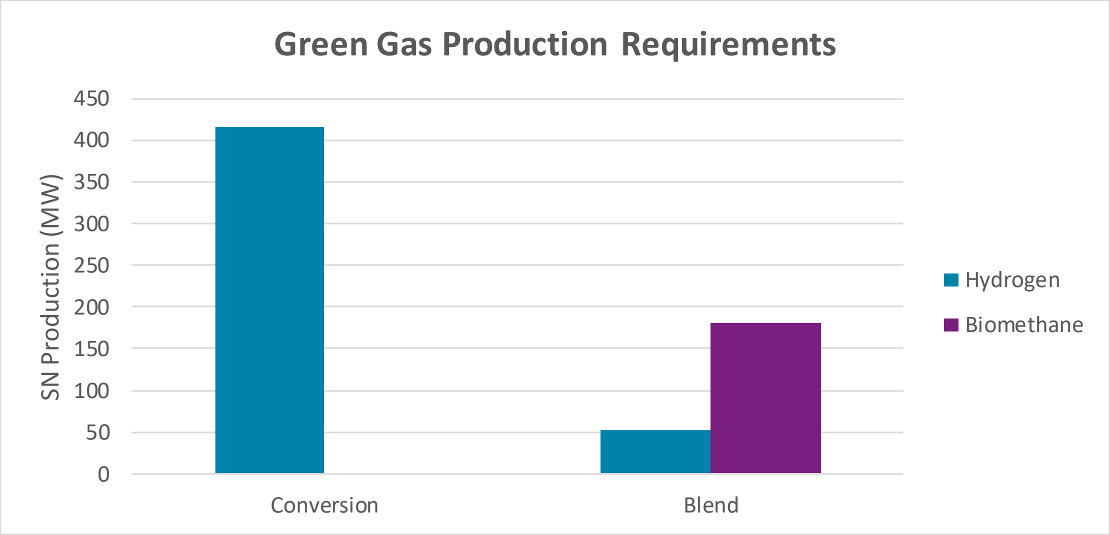
The operational implications associated with the forecasted changes for the SN electricity network the as described in the reference scenario, Section 6.4.

8.5 Investment Implications

The investment implications resulting from the green gas scenario span both electricity and gas. The electricity investment implications, concerning both installed capacity and network investment, are as described in the reference scenario, Section 6.5. The investment implications associated with the gas network are dependent on the balance of biomethane and hydrogen deployment.

The required level of compliant SN green gas production for each option, assuming full conversion of the SN industrial cluster in the blending option, is shown below.

Figure 8-4: SN Green Gas Production Requirements in 2050



Given that the likely source of hydrogen in either option would be from Steam Reformation (SMR) or Autothermal Reformation (ATR) located on the coastline of the UK to provide access to CCUS infrastructure, for the SN area to provide its 'fair share' of green gas production it would need to concentrate on biomethane production:

1) The total production quota of green gas to achieve compliance through conversion would be 420 MW,
2) The total production quota of green gas to achieve compliance through blending would be 230 MW.

The common investment requirements for options would be the generation of hydrogen transmission infrastructure. The principal difference between the options with regards to national investment would be in generation assets, as the biomethane supporting by blend option would require less green gas production than the full hydrogen conversion option. The below table summarises the investment implications of each compliant option within a Green Gas strategy.

Figure 8-4: SN Green Gas Investment Comparison

Supply Chain Stage	Biomethane + Hydrogen Blend	Hydrogen Conversion
Supply (MW)	230	420
Transmission	New Build	New Build
Distribution	-	Conversion + Storage
Use	-	230,000 gas boilers

Although economic comparisons are outside the remit of this report, based on the technical requirements for compliance that result from each green gas option it is likely that a strategy based on biomethane with hydrogen blending would require less investment than a hydrogen conversion strategy.

9.0 SUPPLY HYBRID SCENARIO

9.1 Modelling Approach

The Supply Hybrid scenario explored whether compliance could be achieved by balancing the deployment of low-carbon electricity and low-carbon gas. This scenario represents a decarbonisation strategy that is still supply-driven, but looks to balance changes between the electricity and gas networks to achieve compliance.

As the reference point already has a near complete conversion of road transport to EVs, the necessary carbon reduction required to achieve compliance with the SN area must come from heat. Therefore, the Supply Hybrid scenario sought to balance the deployment of green gas with the electrification of heat via the installation of ASHPs plus flexible generation to satisfy peak demands.

The green gas approach within the Supply Hybrid scenario sought to minimise disruption to consumers, therefore a hydrogen blend plus biomethane approach was taken to be the prevailing strategy. The scope of green gas deployment was:

1) A 20 $\%_{vol}$ blend in the LTS for commercial and domestic use;
2) A 50 $\%_{energy}$ conversion of industrial consumers; and
3) Utilisation of the natural allocation of biomethane within the SN area, based on UK feedstock availability.

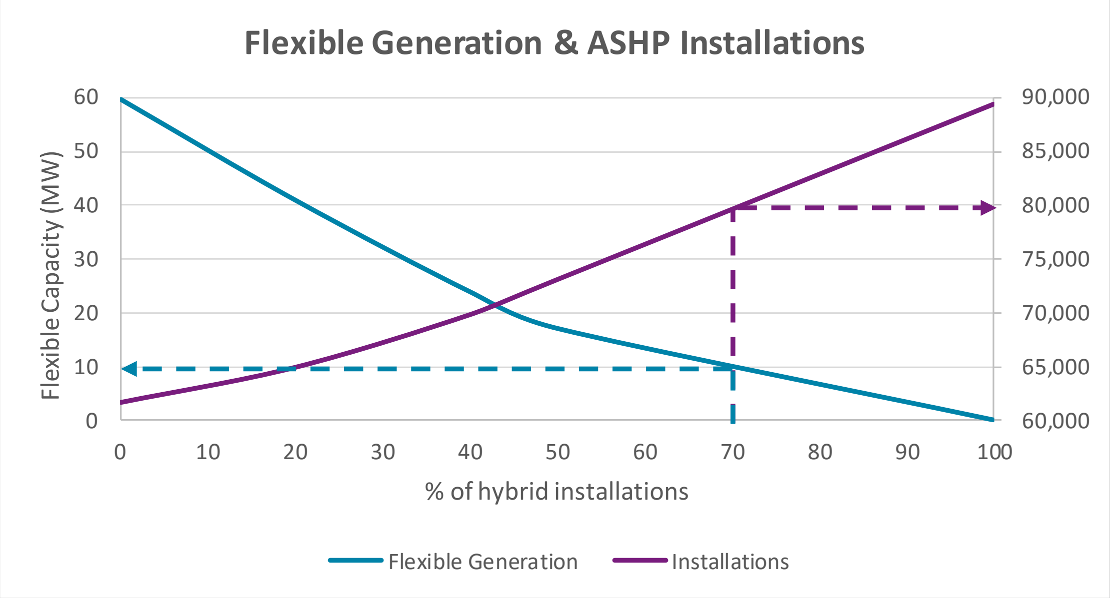
Following definition of the green gas strategy, compliance was then achieved by installing ASHPs and increasing flexible generation if needed. The installation of ASHPs was varied between 100% of installations replacing gas boilers to 100% of installations complementing gas boilers as hybrid systems which then allowed the system effect on flexible generation requirements to be established.

This modelling approach is akin to one of the recommendations from the 2018 CCC Hydrogen report[11] which outlined a decarbonisation pathway via deploying hydrogen in tandem to hybrid heating systems.

9.2 Impact on Consumers

The impact that a Supply Hybrid scenario has on consumers is dependent on the nature of ASHP installations, whether they are stand-alone or hybrid systems. As the proportion of energy supplied by the electricity network to a stand-alone ASHP is greater than a hybrid system, and the carbon intensity of electricity is forecasted to be lower than gas in 2050, installation of a stand-alone system yields greater decarbonisation than a hybrid system. Flexible generation requirements increase for stand-alone systems as peak demand still be met through the electricity network. Although the Pathfinder model indicates that most of the incremental peak demand is met by gas turbines, other smart solutions such as vehicle-to-grid provide a proportion of the peak demand. The balance between additional flexible generation and the number installations required to achieve compliance, given if they are stand-alone or hybrid systems, is shown below. Included in the chart is an example of how to interpret the data.

Figure 9-1: Flexible Electricity Generation Implications of ASHP Installations



All of the data points on the above chart indicate compliance within the SN area, the above chart represents the key trade-off within the Supply Hybrid scenario to achieve compliance, based on the output of the Pathfinder model. The process required to interpret the data is:

1) Define the proportion of ASHPs to be hybrids (x-axis), in the example it is 70%;
2) Track up from the x-axis to the blue line and then to the left y-axis to determine the necessary level of flexible generation required to ensure peak supply, in the example this is 10 MW;
3) Track up from the x-axis to the purple line and then to the right y-axis to determine the number of installations required to achieve compliance, in the example this is 80,000;
4) Therefore, in the example given, compliance could be achieved within this scenario by installing 56,000 hybrid ASHPs (70% of 80,000) and 24,000 stand-alone ASHPs (30% of 80,000), along with 10 MW of flexible capacity.

There is a clear trade-off between flexible generation capacity and the number of installations required to achieve compliance, based on the proportion of those installations that are hybrid systems. The necessary disruption to consumers is a subtle balance as well, given that:

1) Replacing a gas boiler with an ASHP is a more disruptive activity for the customer undertaking the replacement due to typically needing more alterations such as larger radiators or underfloor heating; but,
2) The total number of ASHP installations necessary to achieve compliance reduces as the proportion of full conversions increases.

A minimum personal disruption strategy would promote installation of hybrids, in which case 90,000 installations would be required to achieve compliance within the SN area with no additional flexible generation. A minimum community disruption strategy would likely promote full conversion systems, in which case 60,000 conversions would be required to achieve compliance within the SN area, along with 60 MW of flexible generation. A more detailed study on the relative merits of hybrid systems and stand-alone ASHPs is the Freedom project[23]. Which demonstrated the potential for hybrid ASHP solutions as a comparative technology to ASHPs when viewed from the perspective of both network implications and consumer decarbonisation, especially for off-grid homes with high counterfactual heating costs. The Pathfinder model yields a greater system decarbonising effect due to ASHPs relative to hybrids because the structural logic of the model:

1) If total electricity demand is greater than total low carbon generation from major generators, then,
2) The first decision the model takes is to switches hybrid systems to use the gas boiler,
3) The next decision is to draw upon available vehicle-to-grid and commercial batteries (which both only charge during times of excess low carbon generation),
4) The final decision is to call upon dispatchable generation sources such as OCGT and interconnectors.

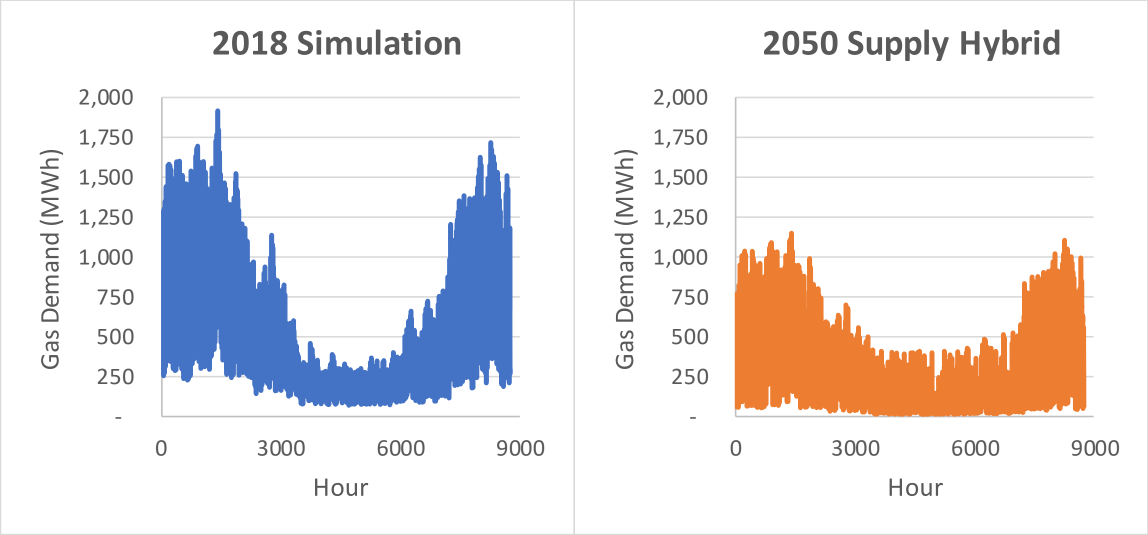
Due to the nature of the calculation methodology, ASHPs are able to access a greater quantity of low carbon electricity relative to hybrid systems and therefore provide a greater decarbonising effect. Assessing sensitivities based on modifying the structural logic of decision making within the Pathfinder model was not part of the scope of this project, however a useful exercise could be to understand the impact of an alternative decision making seriatim and the outturn implications on the relative decarbonising effect of ASHPs and hybrids.

9.3 Impact on Gas Network

The implications for the transmission and distribution of gas within the gas network for the Supply Hybrid scenario are described in the Green Gas scenario in Section 8.3. The basis of the green gas element of this scenario was taken as the ‘biomethane led and hydrogen supporting’ option due to the reduced level disruption to consumers.

The total forecasted gas demand in 2050 within the Supply Hybrid scenario is a balance between the Electrification and Green Gas scenarios, although still lower than current demand due to increased energy efficiency measures. The hourly profile of gas demand within the SN region is shown below.

Figure 9-2: Gas Demand Comparison (SN Area): Supply Hybrid Scenario



The gas demand profile is smoothed out over the year, especially in the winter, due to the adoption of ASHPs and low-carbon electricity generation capacity. There is, however, a forecast increase in gas usage during the summer months. This is due to the reliance of the electricity grid on gas-fired flexible generation to provide power during calm evenings without much vehicle-to-grid capacity available.

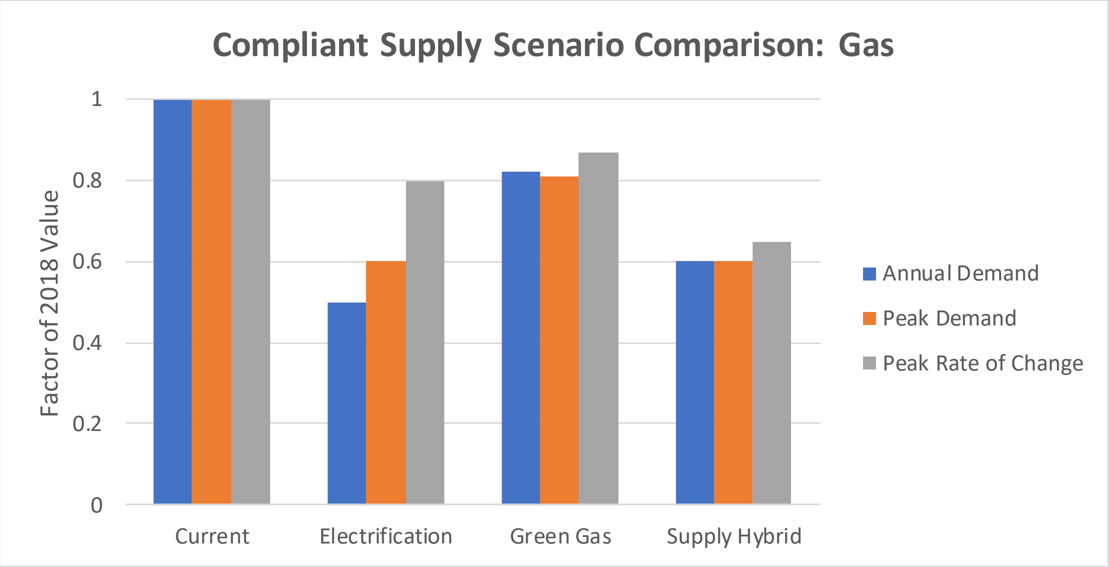
The overarching operational parameters of the gas network resulting from the Supply Hybrid scenario are shown below.

Figure 9-3: Change in Gas Demand (SN Area): Supply Hybrid Scenario

Operational Parameter	2018	2050 (Supply Hybrid)	Change (%)
Average Demand (MW)	500	300	- 40%
Peak-hour Demand (MW)	1,920	1,150	- 40%
Peak rate of Change (MW/h)	560	360	- 35%
Average Diurnal Storage (MWh)	1,720	770	- 55%
Average Diurnal Storage (% of daily use)	14%	11%	- 3%

The forecasted operational envelope for a Supply-Hybrid scenario, as calculated by the Pathfinder model, are contained within the current operational envelope of the gas network supplying the SN region. Consideration should however still be given to the implications for gas forecasting and commercial offtake arrangements, as the Pathfinder output indicates a greater influence of flexible generation on gas demand than current operation. A relative comparison between the current and expected operational envelope from the Supply driven compliant scenarios is given below.

Figure 9-4: SN Gas Network: Supply Scenarios Compliant Comparison



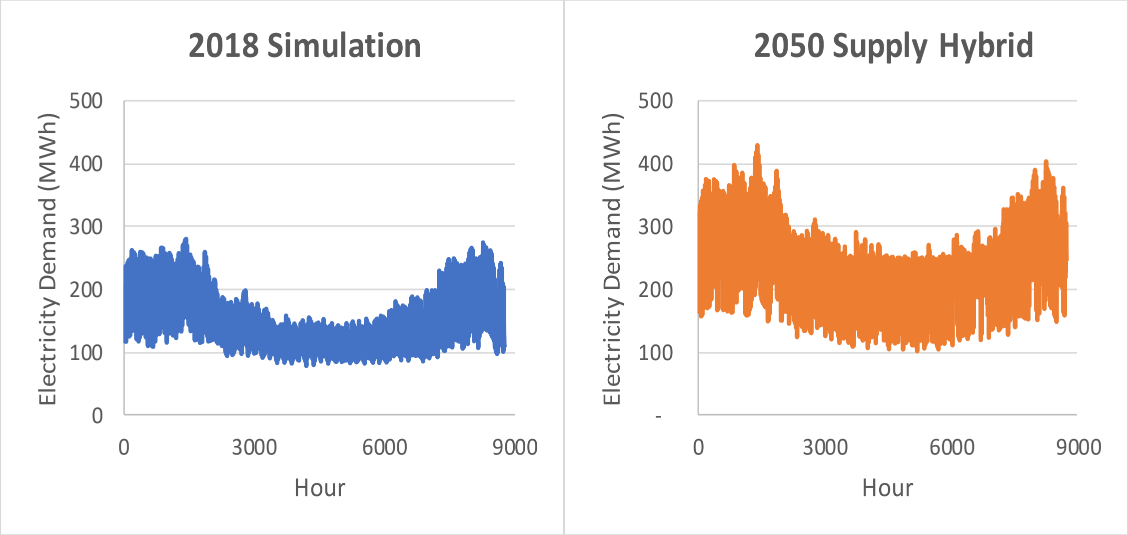
All three strategies result in a net reduction in gas usage and fall within the current operational envelope of the gas network. The challenges of implementing such a strategy would principally be around gas forecasting and variable diurnal storage requirements, along with potential re-compression up LTS pressure tiers to facilitate inter-seasonal biomethane storage. An Electrification strategy results in the lowest gas demand and a Green Gas strategy maintains the highest gas demand. However due to an overarching increase in energy efficiency, the absolute gas demand in all three compliant scenarios would be less than current demand.

Given that all three compliant supply-driven scenarios largely fall within the current gas network operational envelope, the lowest cost supply-driven scenario with regards to network upgrade would be determined by the relative impact each scenario has on the electricity network.

9.4 Impact on Electricity Network

The operational implications for the SN electricity network as a result of achieving compliance via the Supply Hybrid strategy are not significantly different to the reference scenario, given that the additional decarbonisation required to achieve compliance is balanced across the electricity and gas networks. The forecasted hourly electricity demand of the SN region within the compliance Supply Hybrid scenario is shown below.

Figure 9-5: Electricity Demand Comparison (SN Area): Supply Hybrid Scenario



The overall electricity demand is still forecasted to be greater than the current demand, primarily due to the electrification of road transport that is forecasted. A large proportion of the volatility forecasted in the Electrification scenario is removed due to:

1) The reduced requirement of electrifying heat as a result of green gas deployment; and
2) The hybridisation of ASHP installations reducing peak electricity demand.

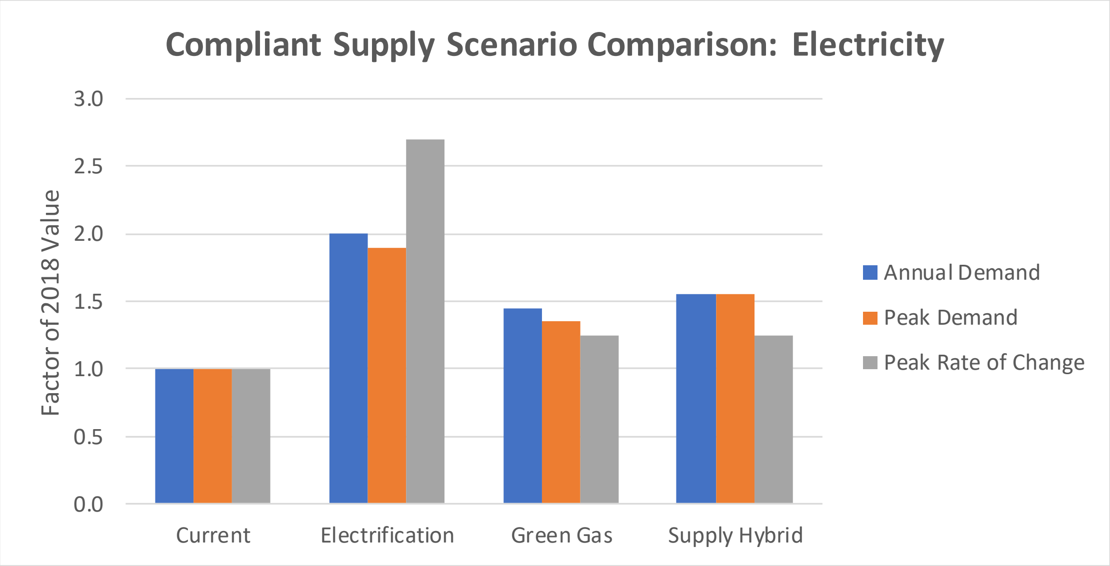
The resulting operational parameters of the electricity network that would be expected as a result of achieving compliance through a Supply Hybrid strategy are shown below.

Figure 9-6: Change in Electricity Demand (SN Area): Supply Hybrid Scenario

Operational Parameter	2018	2050 (Supply Hybrid)	Change (%)
Average Demand (MW)	150	230	+ 55%
Peak-hour Demand (MW)	280	430	+ 55%
Peak rate of change (MW/h)	55	70	+ 25%
Annual Inertia	70%	53%	- 25%
Minimum-Hour Inertia	45%	20%	- 55%

The expected changes in the electricity network operation envelope due to a Supply Hybrid strategy being deployed to achieve compliance would necessitate a targeted reinforcement programme within the SN region. A relative comparison of the current operational envelope and the expected operational envelope due to achieving compliance through Supply driven strategies is given below.

Figure 9-7: SN Electricity Network: Supply Scenarios Compliant Comparison



All three strategies result in a need to upgrade the electricity network supplying the SN region; however, the extent of the necessary upgrade varies considerably between supply-driven strategies. Based on the output of the Pathfinder model, an Electrification strategy would be the most onerous with regards to investment relative to a Green Gas or Supply-Hybrid scenario. Particular attention would need to be applied to accommodating the expected increase in the peak rate of change if an Electrification strategy was applied. The compound peak demand growth rates over 5-year RIIO periods until 2050, post the application of smart interventions, to achieve compliance would be:

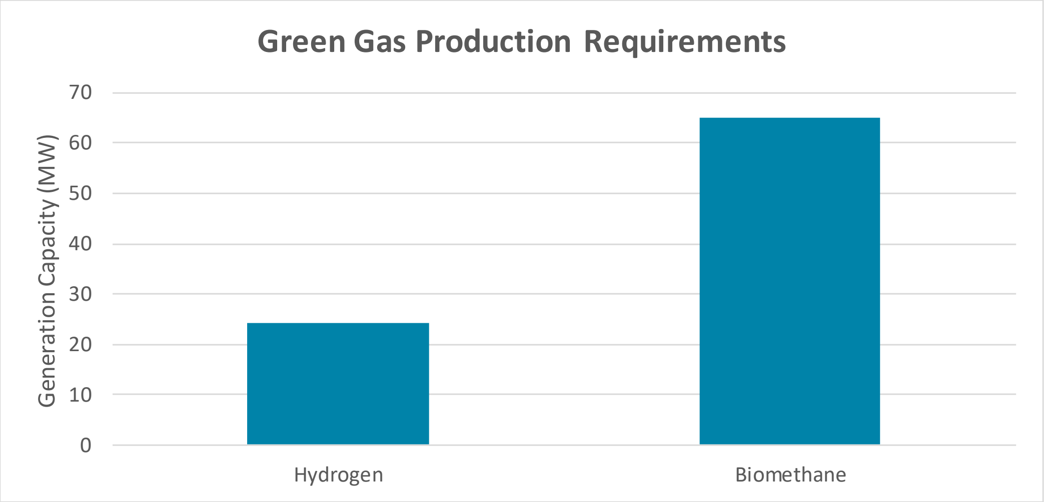
- **Electrification**: 11% compound peak demand growth rate;
- **Green Gas**: 5% compound peak demand growth rate; and
- **Supply Hybrid**: 7% compound peak demand growth rate.

Based on the Pathfinder model output, there is a clear step change in peak demand, annual demand and maximum rate of change between the Electrification scenario and the other scenarios. This demonstrates the advantages of applying decarbonisation strategies that harness the use of both networks.

9.5 Investment Implications

The investment implications of achieving compliance through a Supply Hybrid strategy are a function of the assumed profile of ASHP installations, be they full conversion or hybrid systems. For the gas network, the level of hydrogen and biomethane production required within the Supply Hybrid scenario is shown below.

Figure 9-8: Green Gas Production: Supply Hybrid (SN Area)



For the purpose of developing local compliance targets for the SN region, hydrogen and biomethane capacity will be aggregated into a 'low-carbon gas capacity' target. In support of local compliance, necessary national investment in transmission and distribution would also be required to ensure the national supporting infrastructure is capable of facilitating regional decarbonisation. Assuming that all ASHPs are installed as hybrid systems, the required level of low-carbon electricity capacity is the same the reference scenario, which is 350 MW.

Taking the sum total of necessary changes to supply, distribution and use across both the electricity and gas networks within the SN region for the Supply Hybrid scenario, compliance targets in 5-year increments can be developed. Based on the Pathfinder model outputs, until 2050 the following targets would need to be met every 5-years:

1) Construction of 55 MW of low-carbon electricity capacity;
2) Construction of 15 MW of low-carbon gas capacity;
3) Investment to facilitate a 7% compound peak electricity demand growth rate;
4) Installation of 10,000 hybrid heating systems; and
5) Purchasing of 40,000 electric vehicles.

The 5-yearly compliance targets for the SN region which result from applying a Supply Hybrid strategy are still very ambitious, but potentially more achievable than the necessary targets through solely Electrification or Green Gas strategies. The construction of the necessary low-carbon gas and electricity capacity is ambitious but not unrealistic given the necessary political focus and securement of sustainable biomethane feedstock.

The adoption of EVs is likely to take place naturally due to national policy and the adoption of clean air zones. It is therefore the necessary reinforcement programme and ASHP adoption that would require the most focus to achieve, if compliance was to be achieved through a Supply Hybrid strategy within the SN region. To achieve the necessary investment programme within the electricity grid, both regulators and DNOs would need to be fully engaged to ensure RIIO frameworks were sufficiently robust to deliver the necessary programme of upgrades up to 2050.

10.0 CONSUMER LED SCENARIO

10.1 Modelling Approach

The Consumer Led scenario explored whether compliance could be achieved by consumers owning the decarbonisation agenda and modifying energy use behaviour. This scenario was the first single-vector demand-driven scenario and allows compliant decarbonisation to be seen through the lens of necessary demand and consumer lifestyles changes. The Consumer Led scenario provides another boundary to the conceptual map of compliance, Figure 5-2 - in which the optimum strategy for achieving compliance would exist. The two major consumer led changes that are included within the reference scenario are:

1) The adoption of EVs, resulting in a 90% conversion of personal transport (cars and vans); and,
2) Investment in energy efficient measures up to the net-positive community payback limit of 19%.

To achieve compliance within the SN region by consumers owning the necessary decarbonisation requirements, a number of changes would be required to consumer lifestyle. It was deemed that a fully engaged and driven consumer base could make the following changes:

1) Fully electrify personal transport and optimise aggregate charging behaviour via the adoption of energy tariffs to minimise impact on the electricity network;
2) Install home efficiency measures up to the technical limit of what is achievable - namely 28%; and,
3) Optimise electricity use by modifying appliance behaviour to minimise impact on the electricity network.

It should be noted that an average home efficiency gains of 28% has a material effect on domestic energy usage, as it requires all technical home efficiency measures to be installed ubiquitously across the national housing stock. Therefore, this measure should be seen as ambitious target and more representative of the necessary magnitude of action needed within a Consumer Led scenario, instead of a forecast of actual consumer behaviour. National support policy would be required to achieve such an increase in home efficiency, given that one of the key conclusions of the WWU ‘Consumers Willingness to and ability to pay’ report[22] indicated that “80 percent of consumers would not/could not afford to change to lower carbon heat provision” and “Very large subsidies would be needed to change consumer preferences”.

Beyond the above measures, the final change consumers would also be required to make to achieve compliance would be to reduce their absolute energy demands, resulting in a reduction in the ‘comfort level’ currently enjoyed. This reduction could take the form of reducing electricity demands (appliance behaviour), gas demands (heating and hot water) or both electricity and gas.

10.2 Impact on Consumers

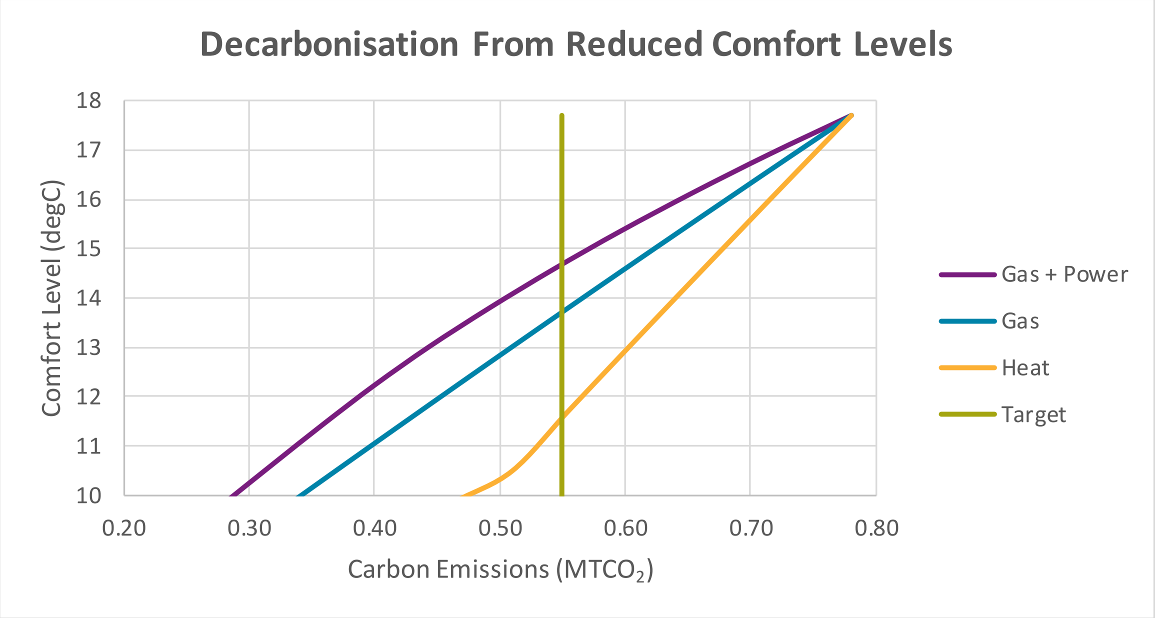
To achieve compliance via consumer energy demand reductions, gas demand would have to be reduced, this is because if electricity demand alone was eliminated compliance still would not be achieved. Therefore, all compliant Consumer Led options contain an element of gas demand reduction, the three compliant options considered where:

1) ‘**Gas and Power’**: Reducing gas and electricity demand equally (as a percentage of demand);
2) ‘**Gas’**: Just reducing gas demand (both heating and hot water); and,
3) ‘**Heat’**: Just reducing heating demand (no reduction in hot water usage).

All energy demand reduction figures were calculated on a per household basis. To determine the consequences of reducing energy demand, the resultant impact on average comfort levels expressed as an average home temperature was calculated. The resultant average home temperature was determined using a heat loss model based on the current average internal temperature of homes[12] and average outside UK temperature data[12]. The annual average temperature difference achieved between internal and external temperatures, by suppling homes with heat, is 8 °C. This difference is due to the average internal home temperature being 18 °C[12] and average external temperature being 10 °C[12]. Therefore, by reducing the heating input by a given proportion, the relationship between decarbonisation and resulting average internal temperatures can be established.

The lowest reduction in comfort level required to achieve compliance results from a consumer base who is willing to equally reduce energy use across appliances, heating and hot water. The intermediate reduction in comfort level required results from consumers not willing to reduce appliance use, but willing to reduce both heating and hot water. The largest reduction in comfort level required results from consumers not willing to reduce appliance use or hot water usage, and only willing to reduce heating. Necessary reductions in comfort level of consumers within the SN region to achieve compliance, once all other changes to lifestyle and installation of energy efficiency measures have been adopted, is shown below.

Figure 10-1: Compliant Comfort Level Reductions



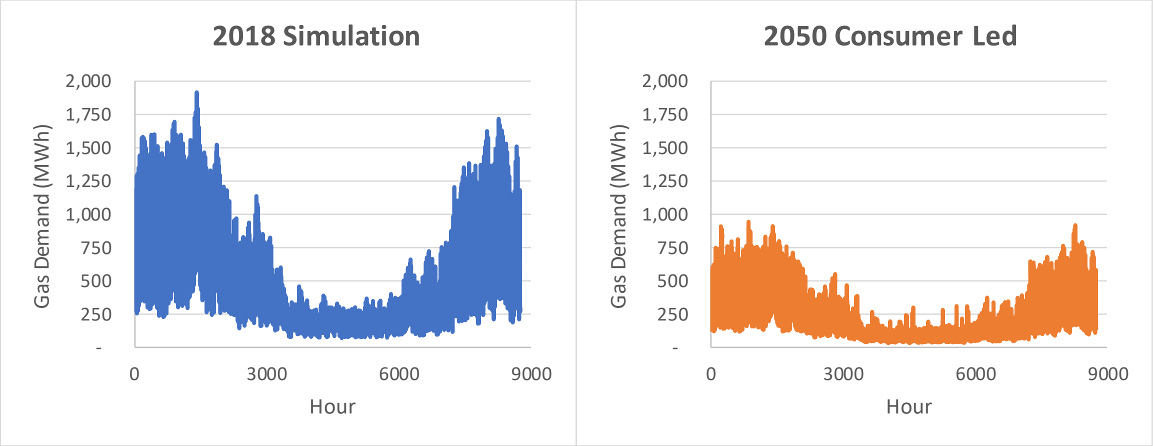
To achieve the regional target of 0.55 $MtCO_2pa$ consumers within the SN region would have to reduce average home temperatures to between 12 – 15 °C, depending on which lifestyle modification measures were deemed acceptable. This reduction represents a large change to consumer comfort levels and potential risk to health, given official NHS advice is to maintain homes at a minimum average temperature of 18 °C[13]. The most onerous reduction in comfort level results in an average home temperature of 12 °C, which was the average home temperature of a UK household in 1970[12].

The necessary personal financial investment and comfort level burden required to achieve compliance via a Consumer-Led strategy would likely be extremely difficult to achieve, given today's lifestyle of comfort and convenience currently enjoyed. The least onerous on comfort levels is the 'gas and electricity' option as this change requires consumers to accept the lowest change to average home temperatures, namely a reduction resulting in average temperatures of 15 °C.

10.3 Impact on Gas Network

The implications for the gas network within a Consumer-Led compliance scenario are dependent on the option of acceptable behaviour modification. Assuming the option which requires the smallest change to home temperatures, namely the option that reduces all energy demands (gas and electricity) equally, the resulting hourly profile of total gas usage is shown below.

Figure 10-2: Gas Demand Comparison (SN Area): Consumer Led Scenario



The fall in domestic gas usage equates to a 40% reduction, this results in a large reduction in the total annual gas usage within the SN region. The operational envelope of the gas network supplying the SN region is shown below.

Table 10-1: Change in Gas Demand (SN Area): Supply Hybrid Scenario

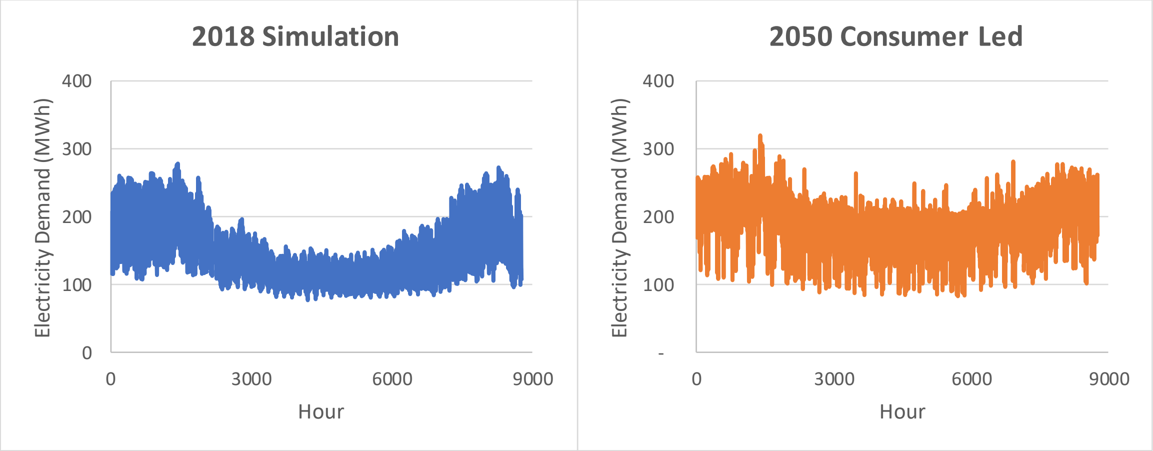
Operational Parameter	2018	2050 (Consumer Led)	Change (%)
Average Demand (MW)	500	250	- 50%
Peak-hour Demand (MW)	1,920	950	- 50%
Peak rate of Change (MW/h)	560	320	- 45%
Average Diurnal Storage (MWh)	1,720	980	- 45%
Average Diurnal Storage (% of daily use)	14%	13%	- 1%

The reduction in gas usage shown in Table 10-1 represents the lowest reduction in gas usage forecasted if compliance is to be achieved via a Consumer Led strategy, as both alternative options of consumer behaviour modification do not include a reduction in electricity usage.

10.4 Impact on Electricity Network

The implications for the electricity network within a Consumer Led compliance scenario are much like the gas network i.e. dependant on the option of acceptable behaviour modification. However, taking the ‘gas and electricity’ reduction option as a working example, the outturn hourly electricity demand profile of the SN region is shown below.

Figure 10-4: Electricity Demand Comparison (SN Area): Consumer Led Scenario



The necessary reduction in domestic electricity demand (excluding EV demand) in this compliant option is equal to the required reduction in domestic gas demand, 40%. This reduction level would be extremely difficult to achieve given the profile of domestic electricity use discussed in Section 12.2, particularly in relation to the split of domestic demand between necessary appliance/device usage e.g. lighting and lifestyle choices e.g. ovens. A reduction of electricity demand on this scale would primarily be contingent on increased efficiency of appliances and home technology, such as LED lighting – as shown in Section 12.2.

The reason why overall demand still increases is due to the effect of charging EVs. The shift in energy supply for personal transport from petrol and diesel to electricity is slightly counteracted by a reduction in electricity usage, however the net effect would still be to increase overall electricity demand. The forecast operational envelope of the electricity network supplying the SN region is given below.

Figure 10-5: Change in Gas Demand (SN Area): Supply Hybrid Scenario

Operational Parameter	2018	2050 (Consumer Led)	Change (%)
Average Demand (MW)	150	190	+ 30%
Peak-hour Demand (MW)	280	320	+ 15%
Peak rate of change (MW/h)	55	80	+ 45%
Annual Inertia	70%	50%	- 30%
Minimum-Hour Inertia	45%	20%	- 55%

The output of the Pathfinder model indicated that, the necessary increase in electricity demand required to achieve compliance via a Consumer Led strategy would equate to, a minimum peak demand compound growth rate of 2% each 5-year RIIO period until 2050. If consumers were unwilling to reduce electricity use then the forecast increase would be greater. It should be noted that the annual demand would be forecast to increase at a greater rate than peak, indicating an increased utilisation of the electricity network.

10.5 Investment Implications

The investment implications required to achieve compliance through applying a Consumer Led strategy would be contingent on the acceptability of behaviour modification options.

For consumers within the SN region, investment implications would amount to:

1) Each car owner replacing their vehicle with an EV; and,
2) Each home owner installing every energy efficiency measure that is technically feasible.

The level of required investment in energy efficient measures will not be realised without a government-backed support programme to reduce the personal cost of energy efficient measures to homeowners. This is due to the scale of intervention that would be required to achieve such an increase. Given that the personal payback limit of home efficiency gains is 12%[7], the following 16% of home efficiency gains would require sufficiency government subsidy to incentivise personal investment. New build regulations would also require adjusting to increase the mandated level of home efficiency measures included within new homes, which would require careful consideration within the context of national and local home build out plans.

The required level of investment for the gas network would be minimal due to each Consumer Led option of consumer behaviour modification resulting in a net reduction in gas demand relative to current operation. However, consideration would need to be given to the nature and daily variability of demand, and any implications for diurnal storage, given the greater forecast increase of flexible generation to provide overnight capacity for EV charging. The required level of investment for the electricity network would be contingent on the option of acceptable behaviour modification, with the Pathfinder model indicating a minimum compound peak demand growth rate of 2% each RIIO period until 2050.

As the Consumer Led scenario did not include adjustments to the installed capacities of generation assets from the reference scenario, the necessary magnitude of investment required to achieve compliance is described in Section 6.5.

Investment would be required on a personal, regional and national scale, to achieve compliance within the SN region through a Consumer Led strategy. Investment would also be needed to fund public awareness and education campaigns. Given that the first barrier to achieving compliance through a Consumer Led strategy is achieving a level of awareness and understanding with consumers to inspire them to make changes in their own lifestyles to reduce carbon emissions. Without a fully engaged public all striving for the same decarbonisation goal, a Consumer Led strategy would not succeed given that all necessary changes would need to be sustained and not reversed – including comfort level reductions. Therefore, to deploy a Consumer Led strategy thought and focus should be directed to raising awareness and ownership of decarbonisation on a personal scale.

11.0 BUSINESS LED SCENARIO

11.1 Modelling Approach

The Business Led scenario explored whether compliance could be achieved by businesses owning the responsibility for decarbonisation and modifying energy use behaviour. This scenario was the second single-vector demand-driven scenario. The Business Led scenario provides the last boundary to a conceptual map of compliance, Figure 5-2. Within the reference scenario the adjustments made to businesses (commercial and industrial) use of energy concerned an increase in the proportion of energy delivered by combined heat and power (CHP) and a level of conversion of internal combustion engine (ICE) HGVs/Buses to non-ICE technology.

To achieve compliance within the SN region via a Business Led strategy a number of changes to businesses use of energy would have to be made. Much like the Consumer Led strategy, the modelling approach incorporated all feasible business decarbonisation decisions within reasonable limits, and then achieved compliance by reducing overall energy demands. The fixed changes assumed were:

1) Electrification of all commercial vans;
2) Full conversion of ICE HGVs/buses to non-ICE;
3) Double the proportion of CHP stated within the reference scenario; and,
4) Convert all industrial gas use to hydrogen via an industrial cluster.

It should be noted that the total number of vans/HGVs/buses were as given by FES Steady Progression in 2050, pro-rated by population. Beyond these changes, the total energy demand was reduced until compliance was achieved. The three options of energy demand reduction were:

1) ‘**Combined’**: Reducing both gas and electricity demand equally (as a percentage of demand);
2) **‘Gas’**: Reducing just gas demand (no reduction in electricity demand); and,
3) **‘Electricity’**: Reducing just electricity demand (no reduction in gas demand).

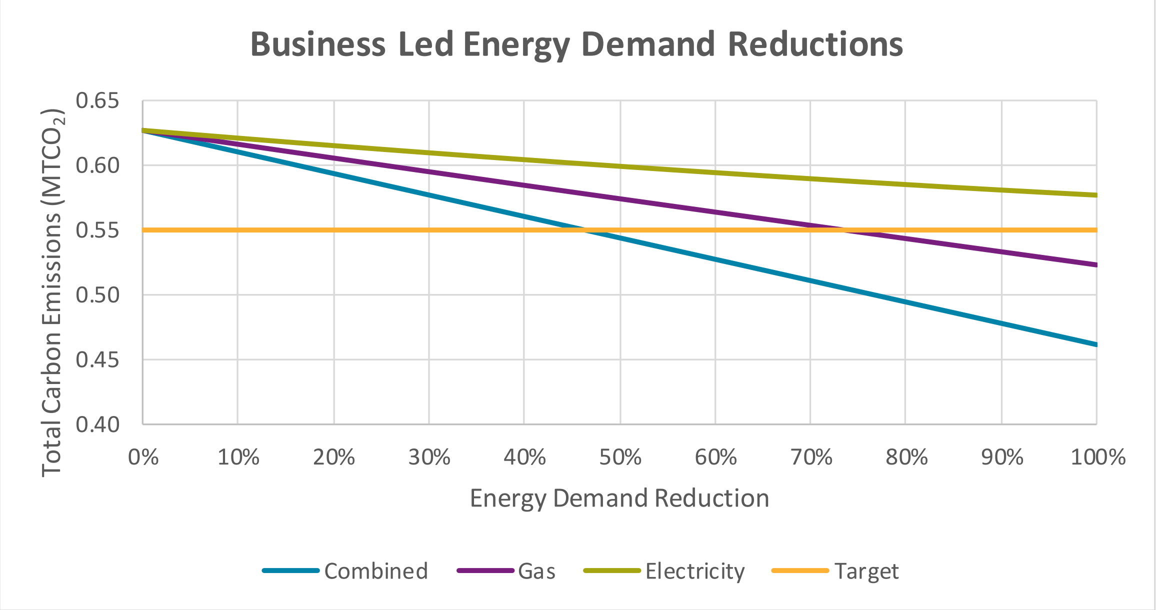
The level of demand reduction required to achieve compliance differed between the three visions. Ultimately the judgement of acceptability of the calculated necessary reductions would have to be made by the UK government and business community.

11.2 Impact on Businesses

Following the decarbonisation of business-related transport, conversion of industrial users to hydrogen and an increase of CHP within commercial and industrial players, the level of energy demand reduction required to achieve compliance would have a material impact on businesses in the UK.

Reducing electricity demand, even to zero, is not able to achieve compliance (as illustrated below). Reductions in both gas and electricity demand are therefore required, with a focus on gas demand reduction. The reduction level required to achieve compliance if businesses reduced both gas and electricity demand equally was lower than if only gas demand was reduced, much like the Consumer Led visions. The resultant emissions implications of each energy reduction option within the Business Led scenario are shown below.

Figure 11-1: Compliant Business Energy Demand Reductions



The minimum reduction in gas demand required to achieve compliance through a Business Led strategy within the SN region is 45%. This level of demand reduction would have a significant impact on production and manufacturing of businesses within the SN region. As gas use within commercial and industrial users is used for both processes (which for many would not be suitable for electrification) and space heating, reducing gas demand would likely result in reduced economic output and potentially make operation untenable. This effect is likely given that businesses will naturally reduce energy use as part of standard operation to drive efficiency and profitability, and must maintain working spaces within legal temperature limit, therefore any incremental energy reduction would unlikely be accommodated without reducing economic output.

Clearly reducing carbon emissions by limiting economic output would not be politically acceptable, given that if replicated on a UK scale, it is likely that a Business Led strategy would move businesses overseas and increase imports of products as the UK business environment would become more challenging – especially for heavy industry and manufacturing. Given the embedded carbon of imports, this strategy would result in the UK meeting its carbon targets, but paradoxically would not result in any net benefit to the environment due to the exporting of emissions.

If businesses were unable to reduce electricity demand then gas demand would have to be reduced by approximately 75% to achieve compliance through a Business Led strategy.

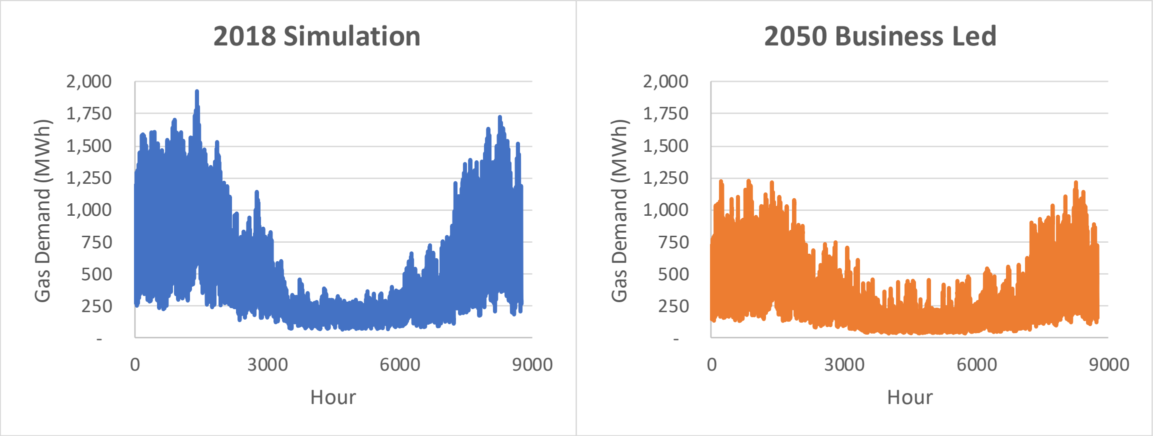
Given the magnitude of modifications required to achieve compliance, both in terms of decarbonising investments and energy demand reductions, is it deemed highly unlikely that compliance could be achieved within the SN region by adopting a solely Business Led strategy.

In any compliant scenario within the SN region, businesses would still have their part to play to ensure carbon targets were met, by investing in low-carbon technology and promoting sustainable lifestyles. However, a significant economic impact would be experienced if businesses were expected to shoulder the burden of full compliance within the SN region.

11.3 Impact on Gas Network

The implication for the gas network of a Business Led strategy is a reduction in commercial and industrial gas demand by at least 45%. For the purposes of discussion, the 'combined' vision of the Business Led strategy has been used to produce the following forecast hourly demand profile of the gas network by the Pathfinder model.

Figure 11-2: Gas Demand Comparison (SN Area): Consumer Led Scenario



The operational envelope of the gas network that results from the deployment of a Business Led strategy to achieve compliance within the SN region falls within the current envelope, therefore no specific upgrade programme would be envisaged to deliver such a strategy.

Given that one of the initial decisions modelled was the full conversion of the SN industrial users to hydrogen, this element of the strategy would be predicated on the construction of a hydrogen supply chain, CCUS infrastructure and transmission system. As the SN region has a smaller industrial base than the UK average, the conversion to hydrogen has a lower decarbonising effect than if deployed elsewhere in the UK. For example, if industry within a highly industrial area was converted to hydrogen, the resultant energy demand reductions required to achieve compliance within a Business Led strategy would be lower.

The operational envelope of the gas network supplying the SN region that results from achieving compliance through a Business Led strategy is as follows.

Table 11-1: Change in Gas Demand (SN Area): Supply Hybrid Scenario

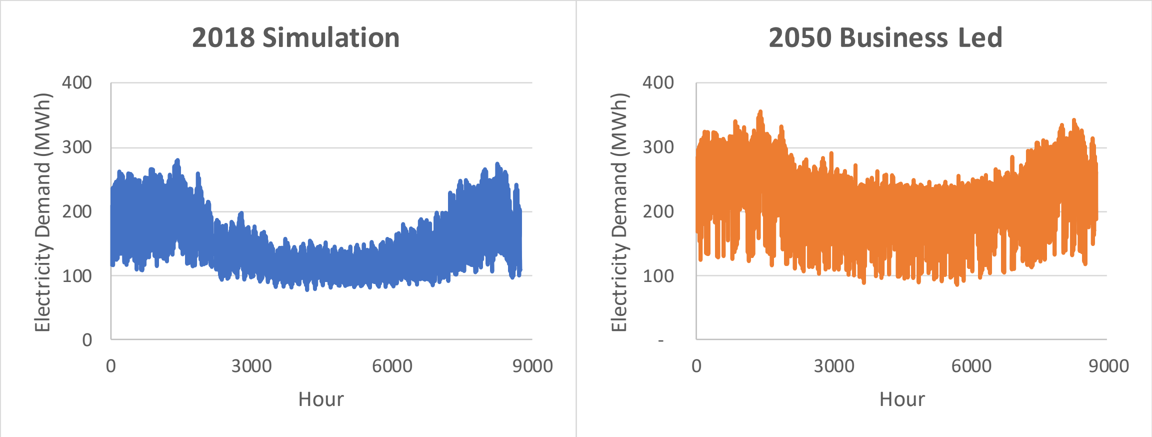
Operational Parameter	2018	2050 (Business Led)	Change (%)
Average Demand (MW)	500	330	- 35%
Peak-hour Demand (MW)	1,920	1,230	- 35%
Peak rate of Change (MW/h)	560	400	- 30%
Average Diurnal Storage (MWh)	1,720	710	- 60%
Average Diurnal Storage (% of daily use)	14%	9%	- 5%

The reduction in gas usage shown in Table 11-1 represents the lowest reduction in gas usage forecasted by a Business Led strategy, as part of the necessary reduction to achieve compliance is absorbed by the electricity network. A greater reduction in the average percentage of diurnal storage was calculated by the Pathfinder model due a 45% reduction in commercial gas use and an increase in electric vehicle adoption. This combination led to the change in daily demand pattern becoming even more focused on overnight flexible generation capacity for EV charging, relative to daily demand.

11.4 Impact on Electricity Network

The operational implications for the electricity network that result from a Business Led decarbonisation strategy would vary depending on the acceptable level of reduction businesses could afford to make. Taking the 'combined' vision as the working assumption for network implications, the following provides the forecasted hourly total demand of electricity within the SN region, as calculated by the Pathfinder model..

Figure 11-3: Electricity Demand Comparison (SN Area): Consumer Led Scenario



The operational envelope required to satisfy the forecast demands on the electricity network would likely necessitate investment to ensure operational integrity in a compliant 2050. The increase in electricity demand forecasted is primarily a function of the almost complete electrification of transport, both personal and business orientated.

The reference point has a 90% conversion of personal transport to EVs and within the Business Led scenario, all business vans and a proportion of buses have also been electrified. The operational envelope of the electricity network supplying the SN region, as calculated by the Pathfinder model, would be as follows.

Table 11-2: Change in Electricity Demand (SN Area): Supply Hybrid Scenario

Operational Parameter	2018	2050 (Business Led)	Change (%)
Average Demand (MW)	150	210	+ 40%
Peak-hour Demand (MW)	280	360	+ 30%
Peak rate of change (MW/h)	55	85	+ 55%
Annual Inertia	70%	50%	- 30%
Minimum-Hour Inertia	45%	20%	- 55%

The necessary increase in electricity demand required to achieve compliance via a Business Led strategy would equate to a compound peak demand growth rate of 4% each RIIO period within the SN region until 2050. Once again, it should be noted that the utilisation of the electricity network has increased, given that annual demand would be forecast to increase by a greater percentage than peak demand. This effect is the result of applying smart interventions to the Pathfinder model, the most significant smart intervention being to optimise the ratio of constrained vs unconstrained EV charging to minimise peak demand. Therefore, the increase in peak demand, as calculated by the Pathfinder model, is a minimum value as it incorporates optimum application of smart interventions.

11.5 Investment Implications

The investment implications to achieve compliance through deploying a Business Led decarbonisation strategy would equate to each business within the SN region;

1) Investing in non-ICE transport;
2) Investing in CHP facilities;
3) Industrial users converting all gas use to hydrogen; and
4) Reducing total energy demand by a minimum of 45%.

Investment within the gas network would equate to the facilitation of a hydrogen supply for industrial users, however no targeted investment programme was forecast by the Pathfinder model within the existing gas network as the forecast operational envelope falls within the current operational envelope. An investment programme within the electricity grid serving the SN region would likely need to be implemented due to a forecast minimum compound peak demand growth rate of 4% each RIIO period was found.

Much like the Consumer Led scenario, the installed capacity of electricity generation were not altered from the reference point. Therefore, the necessary level of local investment in low-carbon electricity capacity is discussed in Section 6.5. Once the necessary reduction in gas demand has been achieved by businesses to achieve overall decarbonisation compliance, the hydrogen use within the SN industrial cluster would equate to 15 MW. Given that any hydrogen supply would likely not be situated within the SN region, a local target of 15 MW of biomethane capacity could be applied to provide an offsetting ‘fair share’ target for low-carbon gas production.

The largest barrier to achieving compliance through the deployment of a Business Led decarbonisation strategy is the necessary level of energy demand reductions required. It is highly unlikely that a minimum reduction of 45% could be achieved through modification and optimisation. To achieve this level of energy demand reduction, it is likely that a proportion of commercial entities would need to reduce or cease production. Given the impact on the SN community that would result from the required level of business activity reduction, it is deemed unlikely that a solely Business Led strategy would be promoted by policy makers.

12.0 DEMAND HYBRID SCENARIO

12.1 Modelling Approach

The Demand Hybrid scenario explored whether compliance could be achieved by balancing energy use modification between consumers and businesses. This scenario represented a decarbonising strategy that is still demand-driven, but looks to balance necessary changes between consumers and businesses to achieve compliance.

Most of the emissions reduction decisions within the reference point concern actions associated with consumers, which are:

1) An increase in energy efficiency for consumers of 19%, which is the limit of community payback; and
2) Adoption of EVs that results in a 90% conversion of personal transport.

The Demand Hybrid scenario sought to balance the ownership of decarbonisation between consumers and businesses, to allow compliance to be achieved through a demand-driven strategy whilst attempting to minimise the magnitude of necessary change for any one group of consumers and businesses. The modelling approach consisted of replicating the approach of the single-vector demand-driven scenarios, in that;

1) Reasonable actions each party (i.e. consumers and businesses) could take were taken as being adopted; followed by,
2) Calculating the necessary reduction in absolute demand required to achieve compliance.

There are many actions that both consumers and businesses could take to reduce carbon emissions. Both of the single-vector demand-driven scenarios outlined the maximum undertakings each party could adopt, therefore the Demand Hybrid scenario assumed half of the progress was achieved across both consumers and businesses. Each action was taken as half way between the reference point value and the respective single-vector value. For example:

1) EV adoption was 90% in the reference scenario and 100% in the Consumer Led scenario, resulting in a value of 95% being set for the Demand Hybrid; and,
2) Home efficiency gain, which was 19% in the reference scenario and 28% in the Consumer Led scenario, resulting in a 23.5% value being adopted for the Demand Hybrid.

Having set this baseline of ambitious yet reasonable changes, the absolute demand of both consumers and businesses was reduced until compliance achieved. The reduction in demand took the form of three options:

1) ‘**Combined**’: Reducing both gas and electricity demand equally (as a percentage of demand);
2) ‘**Gas**’: Reducing just gas demand (no reduction in electricity demand); and,
3) ‘**Electricity**’: Reducing just electricity demand (no reduction in gas demand).

All domestic energy demand reduction figures were calculated on a per household basis. Much like the Consumer Led and Business Led scenarios, compliance could not be achieved by only reducing electricity demand, this was primarily due to the low carbon intensity of electricity forecast in 2050. Therefore, compliance was determined by reducing gas demand. A smaller demand reduction was possible by reducing both gas and electricity, relative to only reducing gas demand.

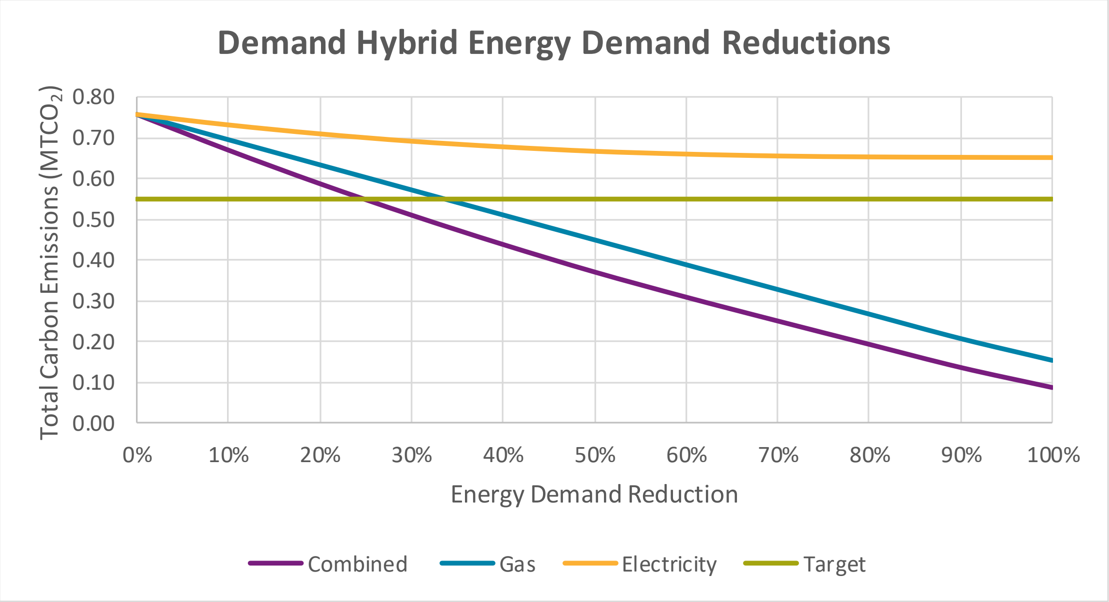
12.2 Impact on Consumers

The implications for consumers within a compliant Demand Hybrid strategy are associated with:

1) Personal expenditure to install energy efficiency measures, given that a 23.5% gain home efficiency would still be incredibly ambitious;
2) Changes to consumer behaviour to distribute electricity use over the day to minimise impact on the electricity network; and
3) Changes to consumer expectations regarding energy use for appliances, heating and hot water.

It was found through the Consumer-Led scenario that the necessary reduction in energy use was a minimum of 45% which resulted in a reduction in average home temperatures to 12 – 15 °C. Following the deployment of the 'half way' measures between the reference scenario and Consumer Led scenario, the following outlines the resultant energy demand reductions required to achieve compliance.

Figure 12-1: Compliant Demand Hybrid Energy Demand Reductions



The minimum reduction in relative demand necessary to achieve compliance is 25%, which corresponds to the 'combined' option of demand reduction. If only gas demand was deemed acceptable to reduce, the necessary reduction would have to be 35% to achieve compliance.

The proportion of gas used for hot water was calculated by analysing the monthly use of gas within households and assuming no gas is used for heating during August, and hot water usage is constant throughout the year. This led to heating corresponding to 65% of domestic gas usage. Applying this factor to the results derived from the Demand Hybrid scenario leads to the conclusion that, if only heating was deemed acceptable to reduce (no reduction in hot water usage), the necessary reduction in heating demand would need to be 50%.

Applying this range of energy reduction figures to the derived heat loss model results in the following comfort levels required to achieve compliance:

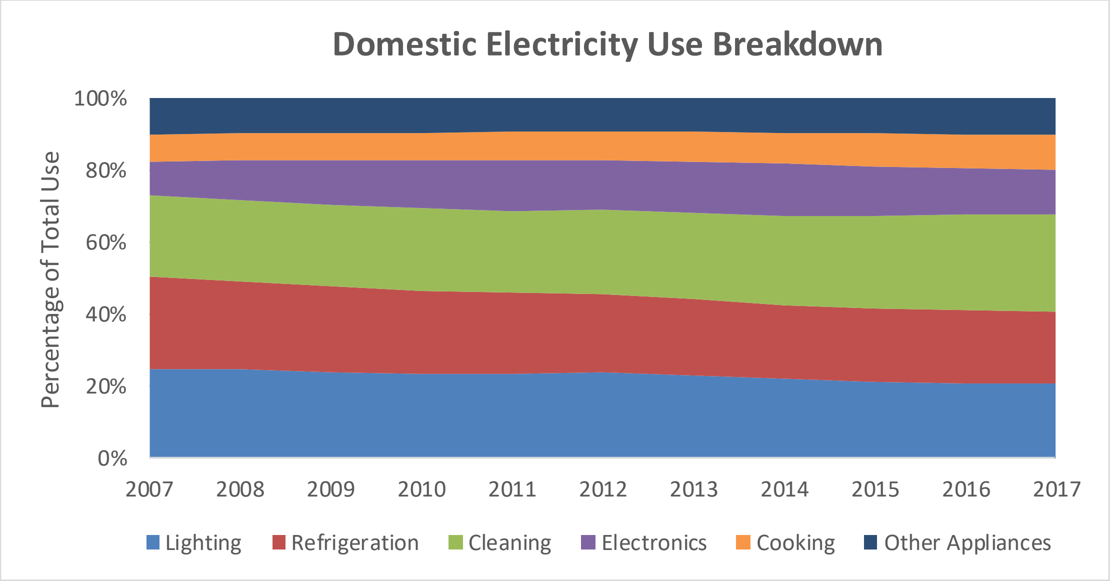
1) **Equal reduction in gas and electricity**: Average home temperature of 16°C;
2) **Reduction in only heating and hot water**: Average home temperature of 15°C;
3) **Reduction in only heating**: Average home temperature of 14°C.

Compliance can be achieved with higher levels of comfort in the Demand Hybrid scenario than in the Consumer Led scenario (14 - 16°C vs 12 – 15°C respectively).

The smallest incremental change to any one consumers lifestyle is the ‘combined’ option, as the necessary demand reductions required for compliance are distributed over electricity, hot water usage and heating. Within this option a 25% reduction in energy demand would be required across all three areas, equating to an average home temperature of 16°C, which was the average home temperature in 1990[12]. An average home temperature of 16°C is still below the NHS recommendation of 18°C, therefore studies would need to be conducted to understand the health implications of reducing home temperatures to this figure.

A 25% reduction in energy use for appliance behaviour would take a concerted effort on the part of consumers with the SN region to adjust behaviour to minimise electricity use and use energy efficiency appliances/devices. A breakdown of domestic electricity use[14] in the UK is given below.

Figure 12-2: Domestic Electricity Use Breakdown



The three largest uses of electricity in a UK household are; lighting; refrigeration and cleaning, which collectively accounted for 75% of domestic electricity use. It is unlikely the consumer demand that each of these appliance categories satisfies would reduce e.g. lighting needs during evenings and maintaining cold food. Therefore, reducing energy demand would likely have to be achieved through the use of efficient appliances/devices such as LED lighting and microwave ovens.

12.3 Impact on Businesses

The implications for businesses to achieve compliance within the SN region from a Demand Hybrid strategy are defined by:

1) Taking a 'half-way' measure between the reference scenario and the Business Led scenario; and,
2) Applying the same energy reduction figures that consumers would be required to achieve.

These changes would equate the following modification in energy demand for businesses:

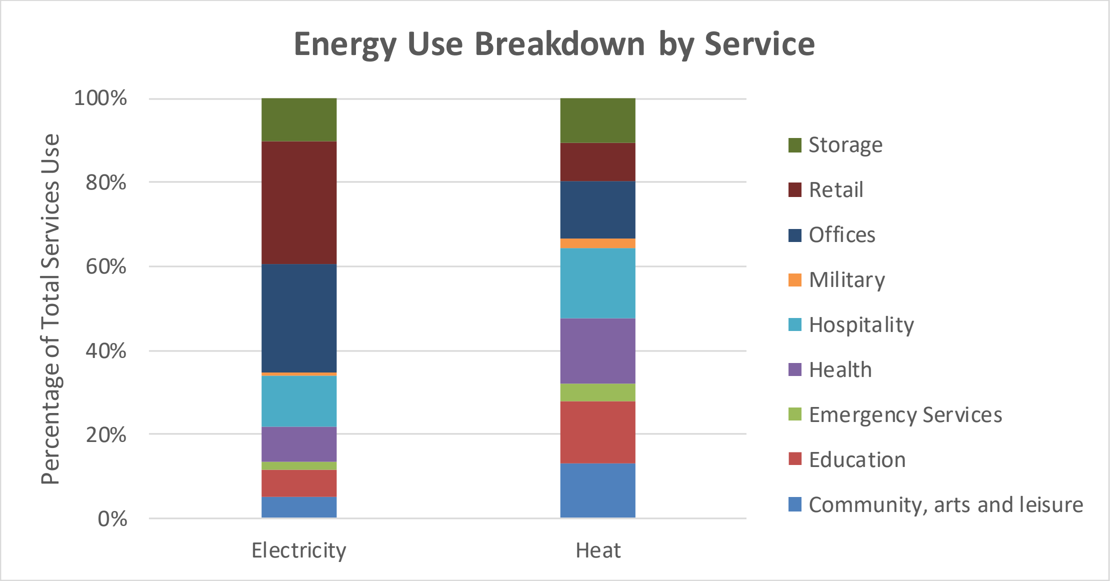
1) Electrifying the majority of commercial vans and converting the majority of ICE HGVs and buses to CNG HGVs;
2) Installing CHP where possible and converting half of industrial gas use to hydrogen; and
3) Reducing gas and electricity demand by 25% or just gas demand by 35%.

The first two required changes would be predicated on the installation of sufficient national infrastructure to support such transitions, for example charging points to allow commercial electric vans to recharge. The only alteration of energy use within the first two changes that is not incremental in nature to forecast changes is the conversion of half of the industrial cluster within the SN region to hydrogen. Therefore, assuming sufficient incentive programmes were initiated on a local and national scale to go beyond the reference point, the only step change to the forecast regulatory landscape would be a hydrogen strategy to enable a hydrogen supply chain and transmission system to be constructed.

The final change that would be required of businesses would be reducing gas and electricity demand by 25% or just gas demand by 35%. Part of the necessary reduction required could be achieved by businesses upgrading machinery to more efficient processes, however within an industrial manufacturing context any efficiency gain would likely be offset by increasing production resulting in minimal net energy saving. The industrial base within the SN region is smaller than the UK average, on a per capita basis, as reflected by the recent announcement the Honda factory closure.

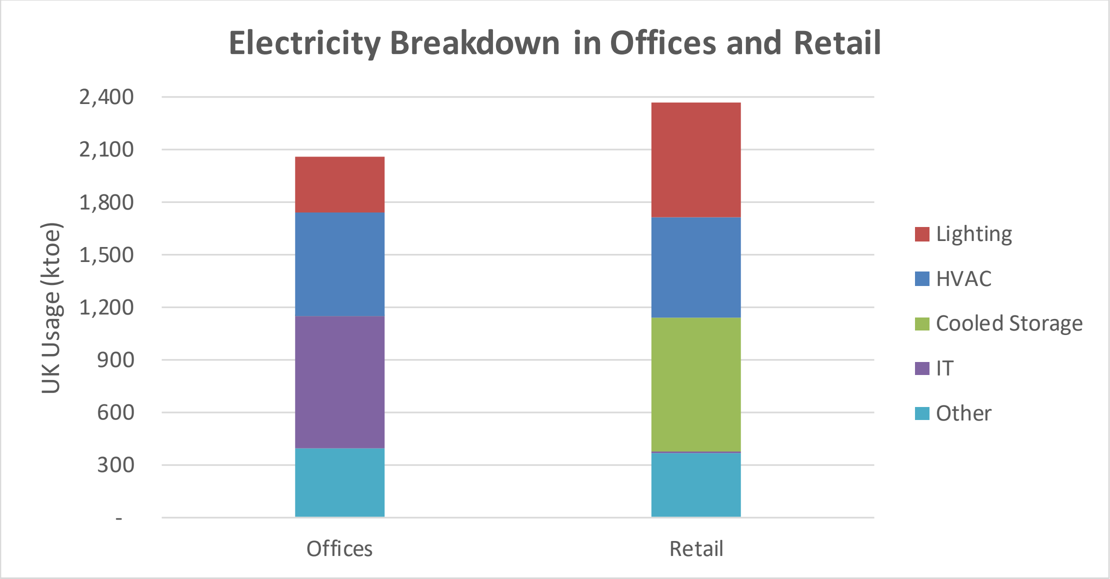
Most of the non-domestic energy use within the SN region, measured by connection capacities, is used within service entities such as retail, health, offices and schools. Therefore, any strategy to reduce the use of energy to achieve an overall saving of 25% across both electricity and gas should be focused on the service industry within the SN region. A breakdown of the UK service sectors energy use in 2017[15], by electricity and gas, is given below.

Figure 12-3: Service Sector Energy Use Breakdown



The two largest users of electricity within the service sectors are retail and offices and the largest gas users within the service sectors are hospitality sector, health and education. A breakdown of the 2017 electricity use of offices and retail in the UK is given below.

Figure 12-4: Electricity Use in Offices and Retail (UK)



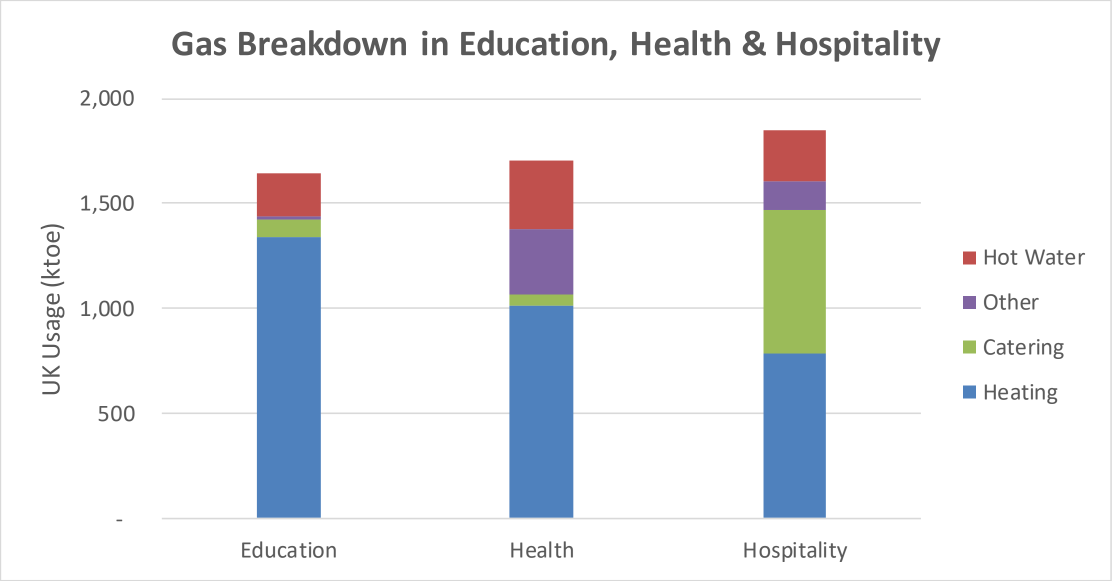
The top three uses of electricity within the office and retail sectors are:

1) Heating, Ventilation & Air Conditioning (HVAC);
2) Lighting; and,
3) Cooled Storage.

Therefore, any directed strategy to reduce commercial electricity demand within the SN region by 25% would need to focus on the above three uses.

A breakdown of gas use in 2017 for the three largest sectors within the services industry is as follows[15].

Figure 12-5: Gas Use in Education, Health & Hospitality (UK)

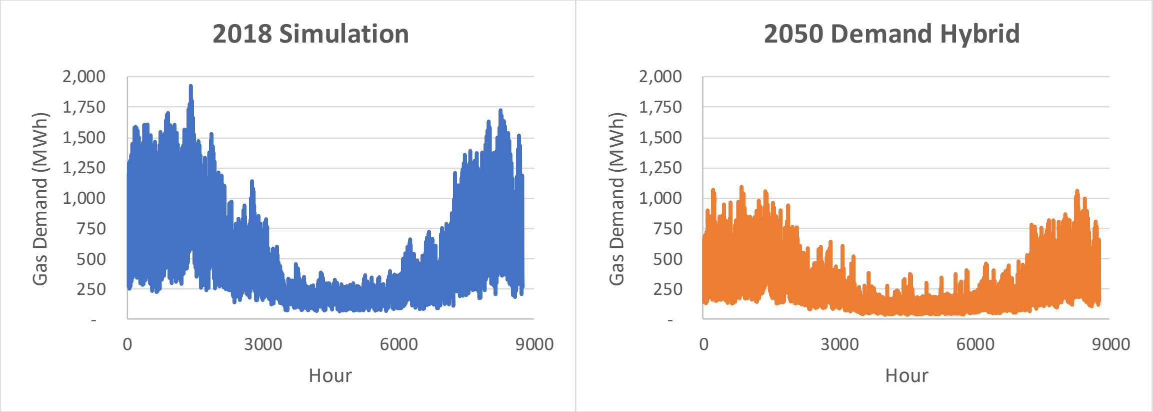


Heating represents 60% of gas usage within the top three gas users of the services industry. Therefore, in the formulation of policy to reduce gas usage within the commercial sector of the SN region, focusing on reducing gas demand for heat in education, health centres and hospitality would yield the greatest gains.

12.4 Impact on Gas Network

The implications of deploying a Demand Hybrid strategy to achieve compliance within the SN region for the gas network are a net reduction in demand, given that an absolute reduction in gas demand across both domestic and commercial users of at least 25% is required to achieve compliance. Based on the 'combined' option of demand reduction, the forecast hourly demand profile of the SN region is as follows.

Figure 12-6: Gas Demand Comparison (SN Area): Demand Hybrid Scenario



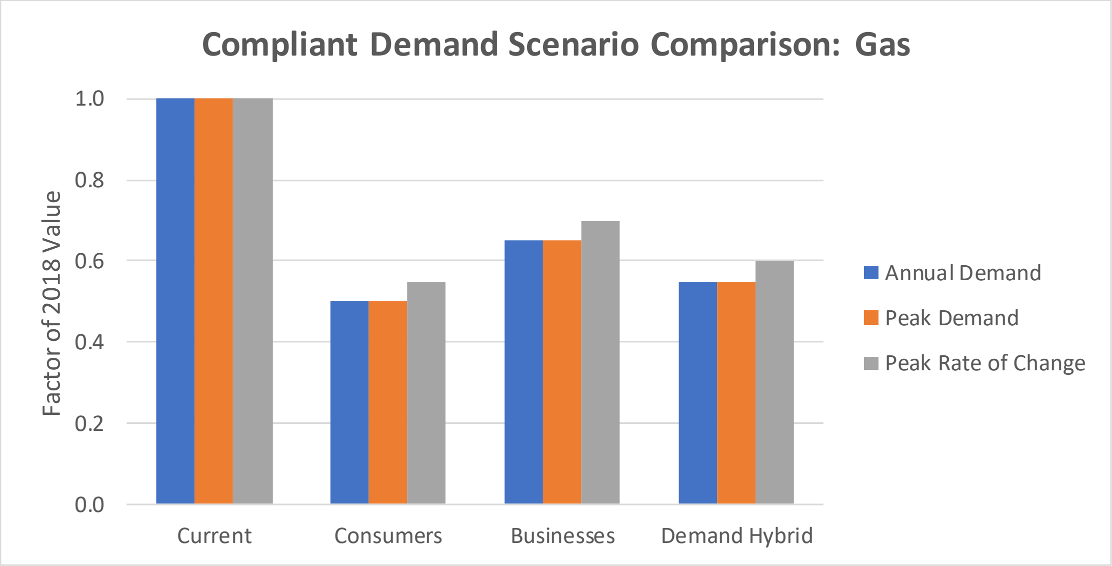
The operational envelope required to achieve the forecast hourly profile can be achieved within the current operational envelope given that both annual and peak demand are forecast to reduce. The operational envelope of the gas network if a Demand Hybrid strategy was deployed to achieve compliance is as follows.

Table 12-1: Change in Gas Demand (SN Area): Demand Hybrid Scenario

Operational Parameter	2018	2050 (Demand Hybrid)	Change (%)
Average Demand (MW)	500	280	- 45%
Peak-hour Demand (MW)	1,920	1,100	- 45%
Peak rate of Change (MW/h)	560	330	- 40%
Average Diurnal Storage (MWh)	1,720	715	- 60%
Average Diurnal Storage (% of daily use)	14%	11%	- 3%

In comparison with the single-vector demand-driven compliance strategies, the Demand Hybrid strategy results in a similar reduction in gas usage and operational requirements. The reason for this is that to achieve compliance through a demand-driven strategy, a reduction in gas demand gives the greatest decarbonisation effect as electricity is substantially decarbonised by 2050. From the perspective of overall emissions, the relative efficiency of gas use in a domestic context to use in a commercial context is a second order factor - overall gas use would need to be reduced by a fairly consistent proportion to achieve compliance. The relative implications for the operation of the gas network through demand-driven strategies, in comparison to current operation, is given below.

Figure 12-7: SN Gas Network: Demand Scenarios Compliant Comparison

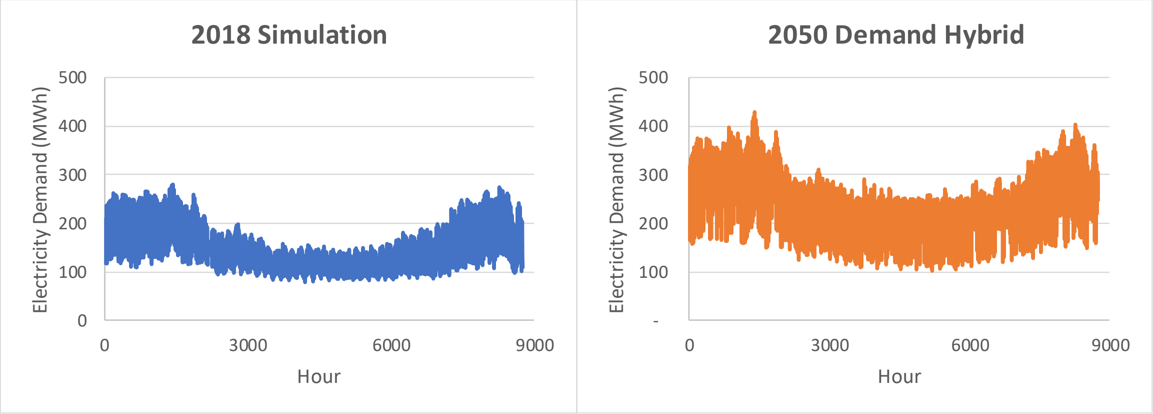


All three demand driven strategies result in a near halving of annual and peak demand relative to current operation. The reason why, the Pathfinder model found the Business Led compliant scenario required a lower reduction in gas usage relative to the compliant Consumer Led scenario, was due to the difference in transport decarbonisation. As the Business Led scenario incorporated a greater level of transport decarbonisation due to the conversion of ICE HGVs to CNG HGVs, businesses had to endure a lower reduction in gas usage.

12.5 Impact on Electricity Network

The implications of achieving compliance through a Demand Hybrid strategy have been derived by assuming the 'combined' option of demand reduction, therefore both commercial and domestic electricity demand would reduce by 25%. Overall the Pathfinder model forecast electricity demand would still rise in comparison to current operation, due to the electrification of transport. The forecasted hourly demand profile of the electricity network to satisfy the SN region is as follows.

Figure 12-8: Electricity Demand Comparison (SN Area): Demand Hybrid Scenario



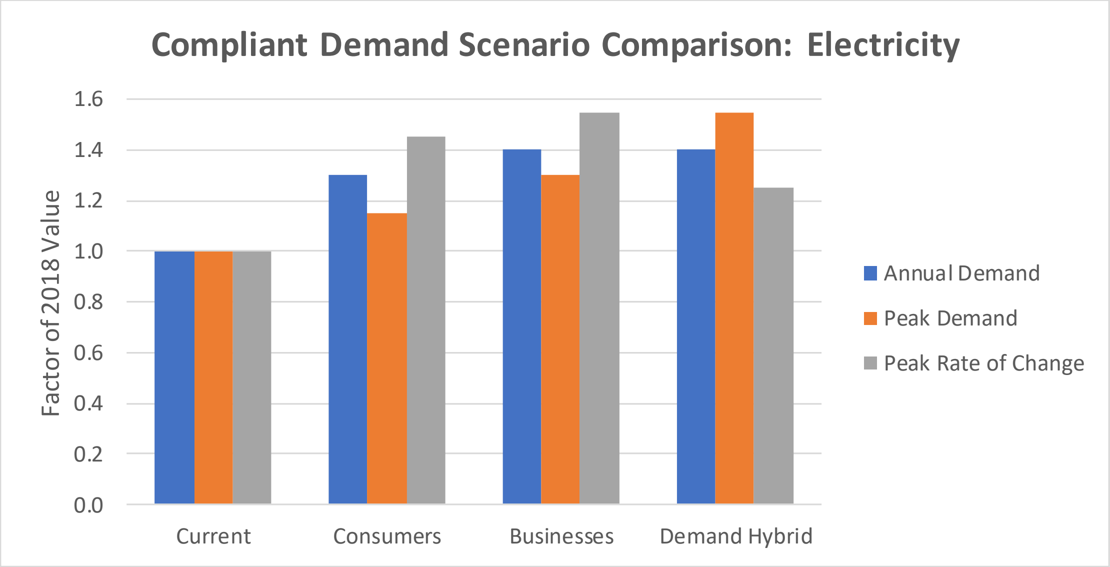
The operational envelope of the electricity network would likely require expanding via an investment programme to ensure sufficient capacity was available to ensure hourly demands could be met through the year within the SN region. The operational envelope of the network, in comparison to the current operation, is as follows.

Table 12-2: Change in Electricity Demand (SN Area): Demand Hybrid Scenario

Operational Parameter	2018	2050 (Demand Hybrid)	Change (%)
Average Demand (MW)	150	210	+ 40%
Peak-hour Demand (MW)	280	430	+ 55%
Peak rate of change (MW/h)	55	70	+ 25%
Annual Inertia	70%	50%	- 30%
Minimum-Hour Inertia	45%	20%	- 55%

In comparison to the other two demand-driven strategies to achieve compliance, the Demand-Hybrid scenario results in a comparable change to the operational envelope of the electricity network supplying the SN region. All three strategies would result in a net increase in both annual and peak demand, primarily due to the constant between them all of at least a 90% electrification of personal transport. The peak electricity demand is greatest in the Demand Hybrid scenario, due this scenario resulting in the lowest reduction in demand to achieve compliance. The relative implications for the operational envelope of the electricity network for each demand-driven strategy is given below.

Figure 12-10: SN Electricity Network: Demand Scenarios Compliant Comparison



All three demand driven strategies would require a proactive investment programme to ensure the electricity grid was capable of supplying the hourly requirements of the SN region. The compound peak demand growth rates for each strategy over each RIIO period time interval, until 2050, would be as follows:

1) **Consumer Led**: 2% compound peak demand growth rate;
2) **Business Led**: 4% compound peak demand growth rate; and,
3) **Demand-Hybrid**: 7% compound peak demand growth rate.

The reason why the compound peak demand growth rate increases from the Consumer Led scenario to the Business Led scenario and then the Demand-Hybrid is due to the mixture of decarbonisation handles with each scenario. As the number decarbonisation handles increases, the energy reduction requirement for each individual handle reduces. Therefore, within the Demand-Hybrid scenario, the electricity demand reduction requirement is lower than both the Consumer Led and Business Led scenarios, resulting in a greater increase in peak demand relative to current operation.

The minimum impact demand-driven strategy for the SN electricity network would be a Consumer Led strategy. However, the success of a Consumer Led strategy would be predicated on unprecedented personal ownership of decarbonisation by consumers within the SN region and a universal acceptance of lower levels of convenience and comfort. The largest impact that a demand-driven strategy could have for the electricity network is a Demand-Hybrid strategy. This is because compliance is contingent on the lowest reduction in demand from businesses and consumers. These two demand-driven strategies highlight a key trade off within any decarbonisation strategy – the less constraining a compliance strategy is for end users, the more constraining it is likely to be for energy networks – and vice versa.

12.6 Investment Implications

The investment implications for a Demand-Hybrid strategy to achieve compliance within the SN region spans consumers, businesses, gas and electricity networks, energy suppliers and policy makers. For consumers further investment in energy efficiency measures beyond the limit for community payback would need to take place. Therefore, this level of personal expenditure would only be achieved in conjunction with a support mechanism to incentivise individuals to make such an investment. A greater level of EV adoption would also be required both for personal use and business use, alongside which businesses would need to convert half of HGVs and buses from ICE to none-ICE.

Both consumers and businesses would need to reduce overall energy demand by a minimum of 25% across both gas and electricity. With regards to consumers, this could be achieved by reducing average home temperatures by 2 °C and by focusing on the adoption of efficient appliances/devices such as; lighting; refrigeration; and cleaning. Consumers would also need to be on correctly designed energy tariffs to incentivise optimum electricity use over the day. With regards to businesses within the SN region, the reduction in gas and electricity use could be achieved by local policy designed to incentivise upgrading of commercial HVAC systems and smart lighting, as well as promoting gas demand reduction measures within offices and publicly owned buildings such as schools and hospitals. Any programme to incentivise reduced heating, either within homes or within public buildings and offices, would require study into potential health implications for those affected.

Concerning the energy networks, no dedicated upgrade programme would be required within the gas network as net demand would reduce in any demand-driven compliance strategy. However, a review of diurnal storage requirement due to a more variable daily gas demand pattern would need to take place. For the electricity network, an investment programme would likely be required to ensure the forecast compound peak demand growth rate could be achieved. This was found by the Pathfinder model to range between 2 – 7% each 5-year RIIO period time interval until 2050.

The installed capacities of low-carbon electricity generation were not changed from the reference point, therefore detail on implications for local targets of construction is described in Section 6.5. The 'fair share' target for local generation of low-carbon gas, to offset the resulting use of hydrogen within the SN industrial cluster, for a Demand-Hybrid strategy was found to be 11 MW.

The greatest risk with any demand-driven strategy is that success would be determined by the aggregate decision-making process of many individual consumers and commercial entities. This risk is material in that policy to incentivise behavioural changes and personal financial decisions to reduce emissions of households or business could be well crafted and appropriate, however, individuals make decisions based on a number of factors, of which carbon emissions is only one. Therefore, the risk of any targeted policy designed to promote decarbonisation via personal empowerment and decision making would be inherently high.

Given the legally binding nature of the UK carbon reduction targets, if a demand-driven strategy is to be the prevailing pathway to compliance, policy development would need to start with minimal delay to understand if the underlying behavioural modification theory is achievable or not. Ultimately an empowered consumer base within the SN region, where each individual feels a personal ownership of decarbonisation, would result in the lowest impact to national infrastructure. However, the route map to compliance through the lens of a demand-driven strategy would be contingent on well crafted, aligned and ambitious policy both at a national and local level to incentivise the necessary individual decisions and lifestyle adjustments necessary to achieve a compliant region, whilst accepting a high level of residual risk to the deployment of a demand driven strategy.

13.0 MULTI-VECTOR SCENARIO

13.1 Modelling Approach

The Multi-Vector scenario explored how demand and supply driven strategies could be implemented together to achieve compliance, in a manner that leveraged the advantageous characteristics of both the gas and electricity network, and did not disproportionately place the burden of decarbonisation on any one party i.e. consumers, businesses or network operators. The Multi-Vector scenario drew upon both the Supply Hybrid and Demand Hybrid scenarios to understand how each approach could alleviate some of the more challenging changes required of the other to achieve compliance.

The approach taken in the Multi-Vector scenario was to select the low-regrets/disruption options from both the Supply Hybrid and Demand Hybrid scenarios and then understand the inherent trade-offs that remained to achieve compliance. The elements of the Supply Hybrid and Demand Hybrid scenarios that were deemed reasonable and low-disruptive vectors for decarbonising the SN region were:

1) **Green Gas**: Maximisation of biomethane to domestic feedstock (pro-rated based on gas demand) which generated a capacity of 80 MW. Alongside a non-disruptive hydrogen blend for domestic and commercial (20 $\%_{vol}$) and half of industrial users converted to hydrogen;
2) **Consumers**: Optimise electricity use behaviour and fully electric personal transport; and
3) **Businesses**: Double CHP, conversion of ICE HGVs/buses to CNG and electrify LGVs.

Home efficiency was kept at the 19% reference point level as this is the limit for community payback - beyond which, there is no societal financial incentive, such as, following quantification of health care costs due to poor air quality. As a 19% increase is already an ambitious target, it was deemed the limit of reasonableness.

The electrification of heat beyond the reference point was not deemed a ‘reasonable’ option due to the implications for the electricity network resulting from road transport electrified. Following the deployment of the above decarbonisation vectors, the remaining decarbonisation to achieve compliance was delivered via more disruptive/challenging routes with equivalencies drawn between them. The three more disruptive/challenging routes were:

1) **Reduce consumer demand**: Resulting in reduced comfort levels for consumers;
2) **Reduce carbon intensity of gas**: Resulting in imported or redistributed biomethane;
3) **Electrify heat plus low-carbon electricity:** Resulting in disruptive changes to consumers and greater impacts on the electricity network.

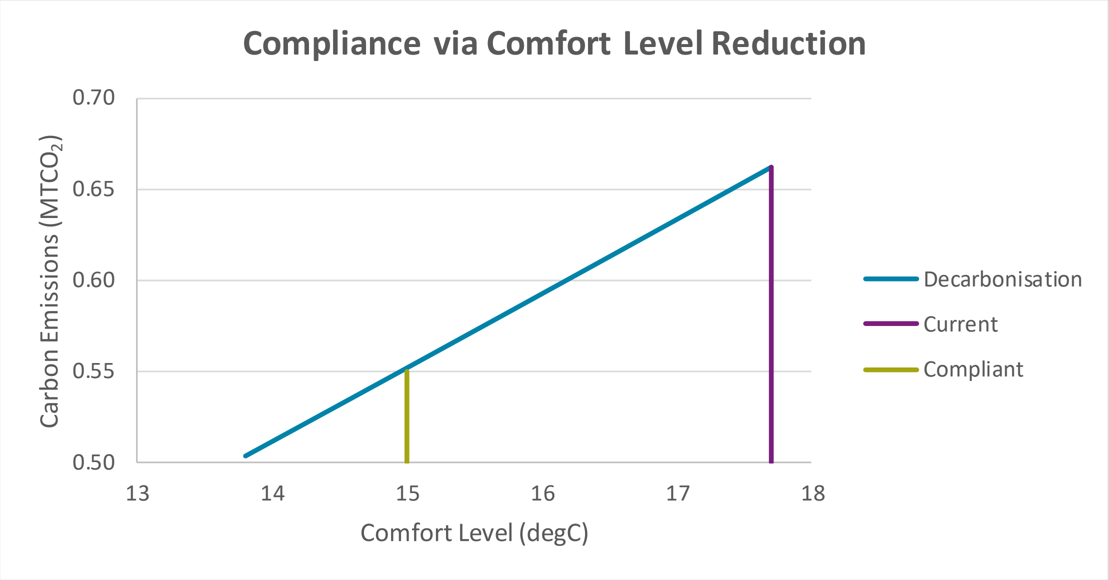
As economic assessment is outside the remit of this study, no economically optimised position between the three challenging routes was determined. Instead the inherent equivalencies between the three were derived based on equivalent decarbonisation. By establishing the equivalencies between the three challenging vectors, the relative gains of each option could be established to inform decarbonisation strategy within the SN region.

13.2 Compliance Equivalencies

The most tangible impact for consumers results from options reduced comfort levels and the installation of electric heating to achieve compliance, given that they have direct implications for consumers and necessitate further consumer changes to achieve compliance within the SN region. Following the implementation of the non-disruptive decarbonising changes outlined in Section 13.1, half of the required emissions reduction between the reference baseline and compliance was achieved. Therefore, the other half of necessary carbon emissions reduction would require a more disruptive change.

The first disruptive change to consumers was to achieve compliance by reduced energy demand. Much like the demand driven scenarios, electricity demand could not be reduced to a level in which compliance was achieved. Given that gas demand is the greatest lever for decarbonisation, the lowest number of changes consumers could make to achieve compliance is to just reduce heating demand. Therefore, for the purposes of the analysis, hot water demand and appliance use were not reduced. The following outlines the necessary changes in consumer comfort level required to achieve compliance following the implementation of low disruption measures.

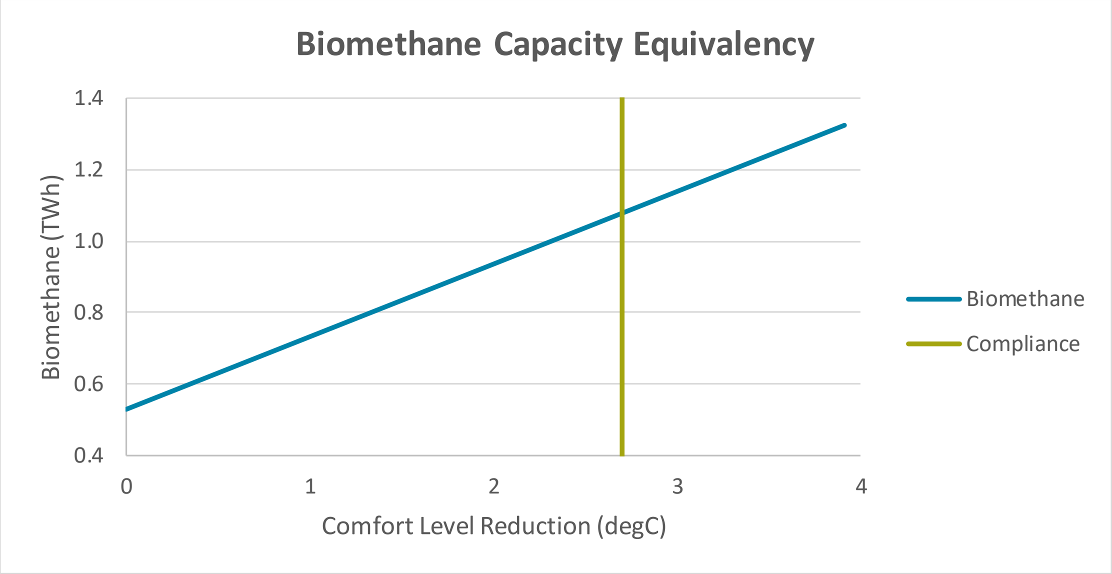
Figure 13-1: Compliance via Comfort Level Reduction: Multi-Vector Scenario



The required reduction in comfort level was calculated using Pathfinder outputs as 2.7 °C, which equates to an average home temperature of 15 °C. The analogous reduction in the Consumer Led scenario was 6 °C which yielded an average home temperature of 12 °C.

To achieve compliance by reducing the carbon intensity of gas would require an increase in biomethane capacity available for gas users within the SN region. This could either be achieved by redistributing biomethane resources from other locations which have achieved compliance via other means e.g. hydrogen cities, or by importing biomethane as a feedstock or ready-to-use gas. Biomethane was chosen as the decarbonising vector for gas over increasing the hydrogen blend supplied to domestic consumers, as blending hydrogen beyond 20 $\%_{vol.}$ would likely involve the mandatory change out of all gas appliances. The initial capacity of biomethane was 0.53 TWh (60 MW) as this is the allocation of UK biomethane based on national feedstock availability of 100 TWh and the SN region's gas usage. The equivalent biomethane capacity required to achieve the same decarbonisation as reduced comfort levels is as follows.

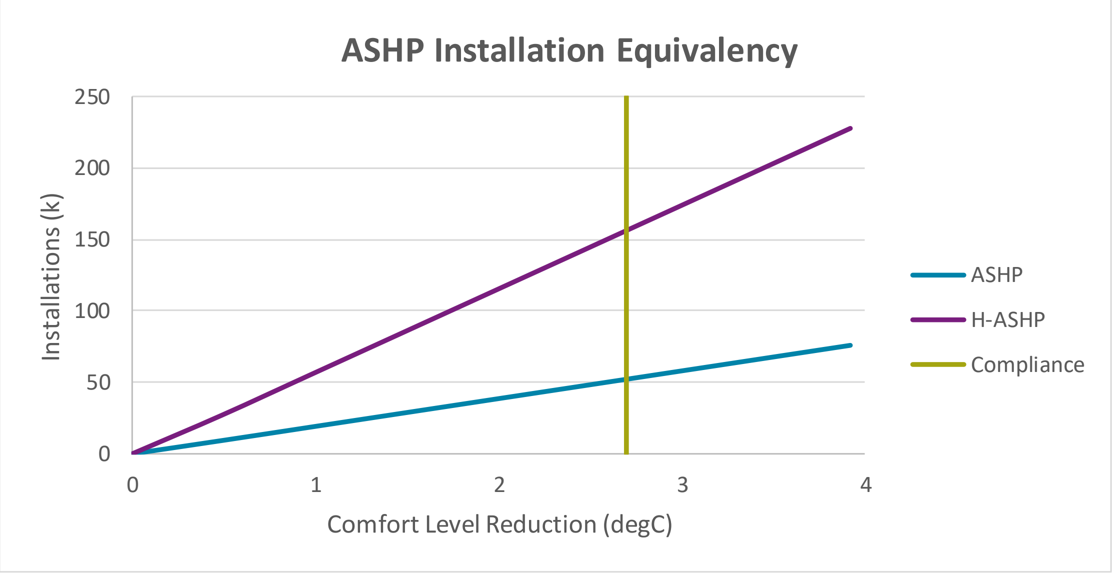
Figure 13-2: Biomethane Capacity Equivalency to Comfort Level Reduction



To achieve compliance via the deployment of additional biomethane capacity within the SN region, additional biomethane equivalent to a reduction in comfort level of 2.7 degC would be required which equates to an additional capacity would be 0.56 TWh. Therefore, if compliance was achieved by solely deploying the biomethane option, the SN region would require a doubling of its natural allocation of domestic biomethane. The additional biomethane capacity equivalent to a 1 degC reduction in comfort levels is 0.2 TWh, or 40% of the SN regions natural allocation.

The final disruptive option would be the electrification of heat via the installation of ASHPs, either as hybrid and stand-alone systems, and the installation of additional low-carbon generation capacity as required. The reference scenario has very low levels of heat electrification and therefore all calculated installation rates are absolute rates relative to today. Both hybrid and stand-alone systems were reviewed due to the difference in disruption and decarbonisation between the two options – hybrid systems are lower disruption to consumers but also have a lower decarbonising effect than stand-alone systems, therefore more are required to achieve the same degree of decarbonisation. The installations required of both hybrid systems (H-ASHP) and stand-alone systems (ASHP) to achieve the equivalent decarbonising effect of reducing comfort levels is as follows.

Figure 13-3: ASHP Installation Equivalency to Comfort Level Reduction



To achieve compliance through the installation of ASHPs within the SN region, either:

1. 160,000 gas boilers would require retrofitting with an ASHP to form a hybrid,
2. 50,000 gas boilers would require replacement with an ASHP stand-alone system.

Both options would require an additional 15% of low-carbon capacity (nuclear, wind and solar), beyond the reference point installations. Marginal generation within the Pathfinder model was assumed to be gas-fired flexible generation due to the baseline low-carbon capacity being saturated with demand from EV charging. In reality, if a hydrogen supply was available this could be used to provide peaking generation, however this could not be modelled within the Pathfinder model. To achieve a given level of carbon displacement within a fossil-fuel marginal generation system, the magnitude of additional low-carbon capacity is independent to the mode in which the additional capacity is used (H-ASHP vs ASHP).

The underlying reasoning that explains the calculated deployment ratio of hybrid systems to ASHPs, to produce the same decarbonising effect, is provided in detail in Section 9.2. Essentially, the underlying logic of the Pathfinder model allows ASHPs to access a greater pool of low carbon electricity via commercial and vehicle-to-grid batteries, which results in ASHPs providing a greater decarbonising effect. Understanding the relative impact of alternative decision making within the Pathfinder model was not part of the scope of this project, but could form the basis future studies.

To achieve compliance using a hybrid ASHP approach, all 160,000 gas boilers in the SN region would require retrofitting with ASHPs to create hybrid systems. To achieve compliance within the SN region by replacing gas boilers with stand-alone ASHP systems, 50,000 gas boilers would require replacing. This figure equates to 30% of the grid-connected gas boilers forecasted in the SN region in 2050.

The equivalent magnitude of each decarbonising vector to achieve the equivalent of a 1°C reduction in comfort levels is given below.

Table 13-1: Compliance Equivalency Summary

Disruptive Vector	Compliance Requirement	-1 °C Equivalency
Reduced comfort level	- 2.7 °C	- 1 °C
Or, additional biomethane capacity	+ 0.56 TWh	+ 0.2 TWh
Or, H-ASHP installation	+ 160,000	+ 58,000
Or, ASHP installation	+ 50,000	+ 19,000

To achieve compliance via the implementation of a Multi-Vector strategy would be contingent on achieving a mixture of vectors that equate to an aggregated equivalency of reducing comfort levels by 2.7 °C. The relative delivery vehicles to achieve the three options would be vector specific and rely upon local policy. A risk-adjusted seriatim of options, based on the number of stakeholders required to take action, could be:

1) Biomethane deployment;
2) ASHP installation; and
3) Reduced comfort levels.

The desired balance of the above vectors would be dependent on local policy direction and priorities. An example balance of disruptive vectors based on an even split between options could be:

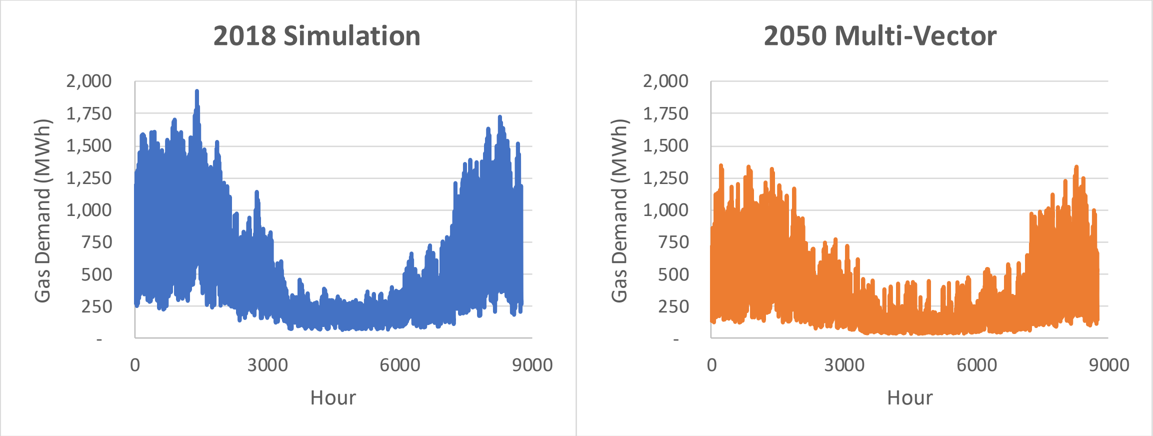
1) Installation of an additional 0.2 TWh (23 MW) biomethane capacity, above the 'natural' allocation of domestic capacity (60 MW), resulting in a total capacity of 83 MW;
2) Retrofitting 58k gas boilers to become hybrid ASHP systems; and,
3) Successful awareness campaign to reduce home thermostats by 1 °C.

The balance of any vectors to achieve compliance would be a challenging undertaking for policy makers, which is a reflection of the magnitude of the overall decarbonisation challenge. However, by balancing challenging vectors to minimise disruption and change to the use of energy and associated supply chain, the roadmap to compliance will be de-risked.

13.3 Impact on Gas Network

The implications for the gas network that results from the deployment of a Multi-Vector strategy would be dependent on the associated policy direction and focus to achieve compliance. A strategy that focuses more on the installation of ASHPs or reducing domestic heating demand would result in a further reduction in both peak and annual demand. Conversely, a strategy that focuses more on the installation of biomethane would maintain a higher gas usage. For illustrative purposes, the example 'equal split' balance of vectors above has been used to generate an example demand profile of the gas network.

Figure 13-4: Gas Demand Comparison (SN Area): Multi-Vector Scenario



The operational envelope required to achieve the forecast hourly profile can be achieved within the current envelop. The forecast system characteristics that define that envelope, in comparison to today's system characteristics, is provided below.

Table 13-2: Change in Gas Demand (SN Area): Multi-Vector Scenario

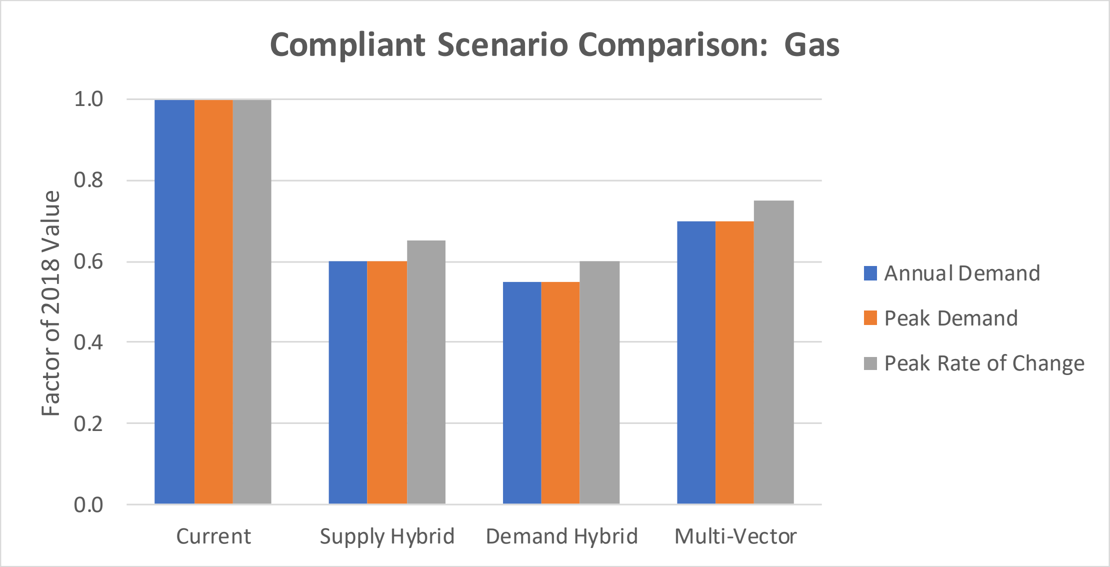
Operational Parameter	2018	2050 (Multi-Vector)	Change (%)
Average Demand (MW)	500	340	- 30%
Peak-hour Demand (MW)	1,920	1,350	- 30%
Peak rate of Change (MW/h)	560	420	- 25%
Average Diurnal Storage (MWh)	1,720	910	- 45%
Average Diurnal Storage (% of daily use)	14%	9%	- 5%

In comparison to both the Supply Hybrid and Demand Hybrid scenarios, the Multi-Vector scenario represents a bridging strategy to understand the system advantages of adjusting both supply and demand in tandem to minimise the necessity to make disruptive changes:

1) The Supply Hybrid scenario utilised non-disruptive green gas vectors followed by the electrification of domestic heat with incremental low-carbon electricity generation;
2) The Demand Hybrid modified consumer and business choices followed by reducing overall energy demand; and,
3) The Multi-Vector scenario utilised all vectors within the Supply Hybrid and Demand Hybrid scenario to a lower extent, as the aggregated effect of making a greater number of smaller changes achieved compliance.

Under both the Supply Hybrid and Demand Hybrid scenario, gas demand fell significantly. In comparison to the two hybrid scenarios, the Multi-Vector scenario yielded a greater use of the gas network as decarbonisation was achieved by neither converting/retrofitting the majority gas boilers with ASHP systems, or by reducing domestic comfort levels drastically. The operational envelope of the gas network from the three strategies is given below.

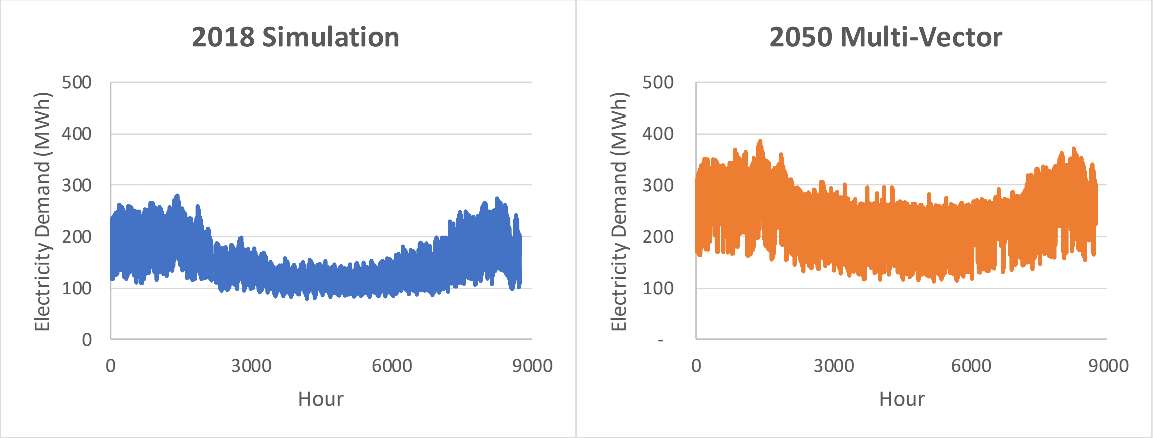
Figure 13-5: SN Gas Network: Scenarios Compliant Comparison



13.4 Impact on Electricity Network

The implications of achieving compliance in the SN area via the deployment of a Multi-Vector strategy on the electricity network are consistent with preceding strategies. The effect of electrifying transport creates a more dynamic system with increased peak and overall demand. On top of the transportation effect, the installation of hybrid ASHPs also contributes to the increased demands of the system, although these effects are minimised due to the balancing of disruptive vectors. For illustrative purpose, the previously proposed example of balanced vectors has been used to forecast the hourly demand profile of the electricity network for the SN region following achieving compliance.

Figure 13-6: Electricity Demand Comparison (SN Area): Multi-Vector Scenario



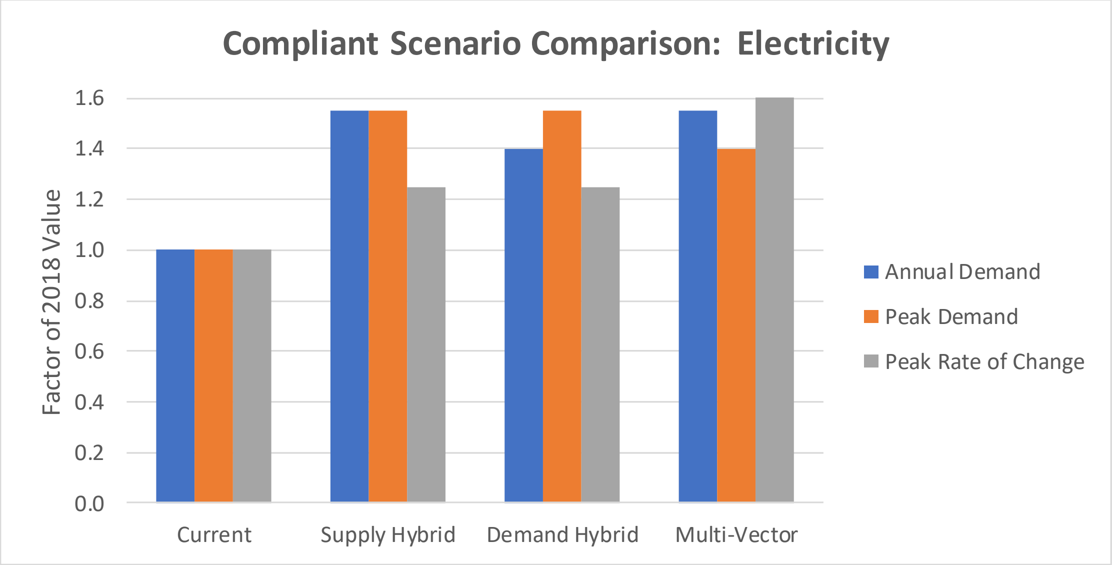
The operational envelope resulting from the above demand profile would require an investment programme to ensure sufficient capacity is available to satisfy the forecasted demand. The resulting profile can be characterised by the following key metrics.

Table 13-3: Electricity in Gas Demand (SN Area): Multi-Vector Scenario

Operational Parameter	2018	2050 (Multi-Vector)	Change (%)
Average Demand (MW)	150	230	+ 55%
Peak-hour Demand (MW)	280	390	+ 40%
Peak rate of change (MW/h)	55	90	+ 65%
Annual Inertia	70%	55%	- 20%
Minimum-Hour Inertia	45%	20%	- 55%

In comparison to both the Supply Hybrid and Demand Hybrid strategies, the implications for the electricity network are relatively consistent. The common factor that results in the consistency is the effect of electrifying road transport. In the example chosen, the Multi-Vector strategy indicates a slightly lower peak demand relative to both the Supply Hybrid and Demand Hybrid. This was primarily due to the installation of hybrid ASHPs, which have a lower peaking requirement on the electricity network than stand-alone ASHPs. The peak rate of change is assessed to be slightly higher than that seen in the Supply Hybrid and Demand Hybrid scenarios due to the assumed electrification of all personal vehicles and all light goods vehicles. Once again this serves to highlight the material effect that electrification of transport is likely to impose on the electricity network. The following graph provides a graphical comparison of the electricity network's operational envelope across the example hybrid and Multi-Vector strategies.

Figure 13-7: SN Electricity Network: Scenarios Compliant Comparison



The above comparison serves to indicate that both demand-driven strategies and supply-driven strategies are likely to result in similar investment implications for the electricity network. The compound peak demand growth rates for each scenario were:

- **Supply Hybrid**: 7% compound peak demand growth rate each RIIO period;
- **Demand Hybrid**: 7% compound peak demand growth rate each RIIO period;
- **Multi-Vector**: 5% compound peak demand growth rate each RIIO period.

The output of the Pathfinder model indicates that the hybridisation of decarbonisation levers provides benefits in enabling constrained to be partially alleviated, as shown by the reduced compound peak demand growth rate from the Multi-Vector scenario. However, due to the impact of the forecast electrification of personal transport, hybridisation cannot eliminate the need to for an investment programme within the electricity network.

13.5 Investment Implications

The investment implications of applying a Multi-Vector strategy would be contingent on the chosen disruptive changes to achieve the final stage of decarbonisation. Policy that focused more towards demand-driven decarbonisation would require a greater level of personal investment by consumers, whereas policy that focused more towards supply-driven decarbonisation would require a greater level of national investment. For the purposes of illustration, the example balance of disruptive changes has been used to outline the necessary investment required to achieve compliance via the deployment of a Multi-Vector strategy.

Consumers would be required to implement the assumed change of increased home efficiency, all car owners would be required to adopted an EV and all homeowners would need to accept a reduction in comfort levels of 1 °C, along with 30% of gas boiler owners investing in hybrid technology. Although this level of change might not seem overly onerous, the decision to accept a lower comfort level would need to be sustained in perpetuity.

Businesses would require modification to operations in the form a greater investment in CHP than forecasted in the reference points, as well as decarbonising transport fleets and 50% of industrial users converting to hydrogen. Once again, this may not appear to be particularly onerous, assuming appropriate support mechanisms were developed to promote business owners to make the necessary investment decisions and to ensure that they remained internationally competitive. However, the ability for businesses to make such decisions would be contingent on national policy as supporting national infrastructure such a hydrogen supply and charging points would be required.

Investment for gas networks would principally be in the form of making the changes required to accept higher levels of both biomethane and hydrogen. Regulatory and technical barriers would need to be overcome to support such development, without which achieving compliance would ultimately have to be achieved by either reducing gas demand or further electrifying heat. No direct reinforcement programme to support peak demand is envisaged, however focusing on operational investment to promote network efficiency with distributed entry connections in a low load factor future would be beneficial. Finally, a review of diurnal storage requirements would be required and an update to gas forecasting methodologies to capture the interaction of overnight flexible generation requirements for constrained EV charging.

Investment for electricity networks would likely take the form of a reinforcement programme with to facilitate a compound peak demand growth rate of 5% each RIIO period. Further network investment would also be required to enable a more dynamic demand profile to be catered for, principally due to the electrification of transport. As a result of the chosen magnitude of ASHP development deployment, local low-carbon investment to provide a 'fair share' of capacity would need to be on the order of 5% greater than those outlined in the reference scenario, Section 6.5. Finally, network investment would be required to ensure that the network remained controllable, given the forecast reduction in inertia coupled with the growth in demand ramp rates.

Taking the sum total of necessary changes to supply, distribution and use across both the electricity and gas networks within the SN region for the Multi-Vector scenario, compliance targets in 5-year increments can be developed. Based on the Pathfinder model outputs, until 2050 the following targets would need to be met every 5-years:

1) Construction of 55 MW of low-carbon electricity capacity;
2) Construction of 20 MW of low-carbon gas capacity;
3) Investment to facilitate a 5% compound peak electricity demand growth rate;
4) Installation of 3,600 hybrid heating systems; and
5) Purchasing of 42,000 electric vehicles.

The investment necessary of policy makers, both national and local, would primarily be in the form of support mechanisms to allow commercial models to be developed – both at a personal and national level. Given the number of vectors used to decarbonise the SN region, the correct design of appropriate support mechanisms would be critical to ensure all of the desired outcomes were achieved.

14.0 SCENARIO COMPARISON

14.1 Impact on Energy Users

The impact of each scenario on consumers is primarily dependent on the nature of the strategy, be it a top-down ‘supply-driven’ strategy or a bottom-up ‘demand-driven’ strategy. The table below summarises the investment required of consumers and businesses within the SN region and necessary lifestyle changes required to achieve compliance. All scenarios included a minimum 19% increase in home efficiency gains and a minimum 90% EV adoption, as these were contained within the reference scenario.

Table 14-1: Scenario Comparison for Gas Network Implications

Compliance Strategy	Technology Investment	Lifestyle Changes
Electrification	60,000 ASHP conversions + 40,000 hybrid installations + 100% adoption of EVs	Adoption of Time of use Tariff (optimise electricity use) + Heating use expectations change due to ASHPs
Green Gas	No technology investment for biomethane + hydrogen blending, or 100% gas boiler replacement for hydrogen conversion	No lifestyle changes
Supply-Hybrid	Between 60,000 – 90,000 ASHP installations (based on stand-alone vs hybrid) + 100% adoption of EVs	Adoption of Time of use Tariff (optimise electricity use) + Heating use expectations change due to ASHPs
Consumer Led	Increase home efficiency gains to 28% technical limit + Installation of energy efficient appliances + 100% adoption of EVs	Adoption of Time of use Tariff (optimise electricity use) + Reduction of home temperatures to between 12 – 15 °C
Business Led	CHP investments + 100% electrification of LGVs + 100% HGV CNG conversion	Energy use reduction of 45% for both gas and electricity
Demand-Hybrid	Increased home efficiency gains to 23.5% + 95% electrification of personal transport and LGVs + 50% HGV CNG conversion	Adoption of Time of use Tariff (optimise electricity use) + Energy use reduction of 25% for both gas and electricity for all consumers + Reduction of home temperatures to between 14 – 16 °C

Compliance Strategy	Technology Investment	Lifestyle Changes
Multi-Vector	58,000 hybrid installations + 100% adoption of EVs (cars and vans) + Conversion to CNG HGVs + Increased CHP usage	Adoption of Time of use Tariff (optimise electricity use) + Reduction of home temperature to 17 °C + Heating use expectations change due to ASHPs

It is clear from Table 14-1 that the potential impacts for consumers and businesses of decarbonisation is wide ranging. Decarbonisation strategies that rely on consumers to make changes to their lifestyles or invest in technology will require aggregate decision making and are likely to require support mechanisms which allow individual consumers to invest. Any policy which promotes a reduction in home temperatures would need to be balanced with studies to understand the potential implications for consumer health.

14.2 Impact on Gas Network

The impact on the gas network that results from the decarbonisation strategies reviewed through this study all face in the same direction – reduced average and peak demand. This is primarily due to the assumed increase in home efficiency within each scenario (minimum 19% gains). Clearly if this gain in home efficiency does not materialise then the forecast reduction in gas usage, as per the Pathfinder modelling, would be lower. The resultant implications for emissions profiles of this sensitivity is explored in Section 6.6.

Table 14-2: Scenario Comparison for Gas Network Implications

Compliance Strategy	Average Demand (MW)	Peak Demand (MW)	Average Diurnal Storage (MWh)
2018	500	1,920	1,720
Electrification	240	1,140	680
Green Gas	410	1,560	1,140
Supply-Hybrid	300	1,150	770
Consumer Led	250	950	980
Business Led	330	1,230	710
Demand-Hybrid	280	1,100	710
Multi-Vector	340	1,350	910

Table 14-2 indicates that all compliant scenarios result in a reduction of gas demand, however the gas network does not become obsolete. Based on the Pathfinder modelling, both average and peak demand would reduce by 20 – 50% relative to current operation, based on the chosen compliance strategy. Although the absolute quantity of diurnal storage is forecast to reduce, the daily pattern of use is forecast to become much more variable due to overnight charging EVs requiring flexible generation capacity.

14.3 Impact on Electricity Network

The impact on the electricity network supplying the SN region of achieving compliance from each of the strategies is shown below in Table 14-3. Directionally all of the scenarios increase both average and peak demand and reduce the average inertia of generation.

Table 14-3: Scenario Comparison for Electricity Network Implications

Compliance Strategy	Average Demand (MW)	Peak Demand (MW)	Average Inertia (%)	Peak Demand Change increase (%)
2018	150	280	70	N/A
Electrification	300	520	50	170
Green Gas	220	380	50	25
Supply-Hybrid	230	430	53	25
Consumer Led	190	320	50	45
Business Led	210	360	50	55
Demand-Hybrid	210	430	50	25
Multi-Vector	230	390	55	65

There is a high degree of variation in the forecast implications for the electricity network, based on the results presented above. From the output of the Pathfinder model, average electricity demand from the SN region is forecast to increase by 25% – 100%. Strategies that favour 'decarbonisation through electrification' have a greater resultant impact on the electricity network. Based on the scenario specific peak demand forecasts, the range of compound peak demand growth rates each RIIO period is 2% – 10% with the Multi-Vector scenario requiring a 5% compound growth rate per 5-year RIIO period.

The average inertia of generation is fairly consistent between scenarios, this is because the generation mixture remains largely unchanged from the reference scenario. The Pathfinder model estimates a reduced average inertia from current operation from 70% to 50%, with the most common minimum-hour inertia of 20%. To accommodate such a reduction in inertia, it is likely that a stability service market would be required to ensure the electricity network remains reliable and stable. The establishment of an inertia/stability market by 2022 has been identified by National Grid ESO as a necessary tool to achieve operation of a zero-carbon electricity network[21].

15.0 RESULTS DISCUSSION

15.1 Transport Electrification

The modelling methodology, which defined a 2050 reference point for the Swindon (SN) area, and then built specific scenarios on top of the reference point to achieve compliance, meant that the underlying effects of the reference point were common within all resulting strategies. The reference point chosen was the Steady Progression FES scenario. Relative to today, the changes inherent in the reference point are themselves significant. They relate to the low-carbon generation mix and adoption of EVs. The necessary level of grid investment to accommodate a mass electrification of transport within the SN area would require targeted DNO RIIO business plans, as well as innovation to operate a much more dynamic network.

The isolated effect of EV adoption is most clearly shown in the electricity network implications for the reference point, Section 6.4. This indicates that EV adoption on the scale forecasted by Steady Progression will require material investment in the electricity network for it to be accommodated. The current, relatively low, level of EV adoption remains manageable within existing network constraints, but it will likely become a major driver for investment in future price controls if the Steady Progression forecast is materialised. Ultimately, a targeted reinforcement and generation installation programme will be required to accommodate the additional load of mass EV adoption.

Consumer adoption of EVs and the resulting effects on the electricity network is likely to make the electrification of heat a greater challenge than it poses when viewed in isolation. This is because mass EV adoption is likely to precede heat electrification, therefore further reinforcement and generation capacity will be required to accommodate heat electrification – as shown in the Electrification scenario, Section 7.4.

The ratio between peak and non-peak charging behaviour was optimised in the Electrification scenario and the resulting implications from the Pathfinder model indicated a 15% reduction in additional peak demand relative to all EVs being unconstrained. The modelling did not consider the effect of fast charging. If fast charging were to be a major charging route for EVs, peak electricity demand would likely increase relative to the scenario calculations.

In summary, if mass adoption of EVs within the SN region materialises (without any material electrification of heat), a network investment programme would be required to accommodate a 5% compound peak demand growth rate each 5-year RIIO period until 2050. This described in more detail in Section 6.4.

15.2 Consumers

Consumers will play a vital role in determining the structure of the decarbonisation strategy for the SN region and more generally. The attitudes and actions of consumers will determine the extent to which demand-driven decarbonisation vectors can play a role in a low carbon strategy. Two primary consumer-based decarbonisation drivers will be; the extent of households to invest; and the willingness of consumers to modify behaviours and expectations.

The extent of consumers' willingness to invest in decarbonising technologies will have a material influence on the future uptake rate of retrofitted infrastructure such as efficiency measures and heat pumps. The WWU 'Consumers willingness and ability to pay' report[22] found that "Initial capital cost is the key factor that influences consumer switching behaviour… the tipping point was estimated at around £3,000 (2015) per dwelling". Therefore, it is highly likely that support mechanisms will be required to promote a high degree of householder investment.

The extent of consumer willingness to modify behaviour has a potential influence on both the electricity and gas networks. These changes are most likely to relate to appliance use and EV charging for the electricity network, and the acceptability of reduced comfort levels for the gas network. Again, it is likely that a direct financial incentive would be required to promote behavioural change. This incentive structure could take the form of a time-of-use tariff to reduce peak demand on the electricity network. However, as the Electrification scenario has demonstrated, modifying the diurnal demand profile of charging behaviour has limited benefits within the context of mass electrification – reducing additional peak demand by up to 15%.

The Consumers section of the Demand Hybrid scenario, Section 12.2, outlined that only around 30% of domestic electricity use is due to demand that could be time-shifted, such as cleaning. The majority of electricity use within the home is determined by hard-to-shift demands such as lighting and cooking. Therefore, although TOUTs are likely to have a positive effect on the energy system by influencing behaviour where possible, the greatest gains in consumer-driven decarbonisation are to be found in energy efficient appliances such as LED lighting.

Consumer behaviour concerning gas usage is likely to be challenging to influence given that heating, cooking and hot water requirements are determined by daily patterns of behaviour and external weather conditions. Consumers' choices around heating supplies will play an important role. Given that, if a consumer chose to electrify their heating supply, use of a hybrid solution or hot water tank could provide system benefit relative to full ASHPs.

The impact of consumer infrastructural demographics is central to system decarbonisation strategy, as technology penetration will be heavily influenced by this. For example, different technology options are available to on-grid homes compared with off-grid homes. Therefore, consideration of alternative technologies to decarbonise consumers must be contextualised by the infrastructural demographic category of consumers being considered. This is explored further in Section 15.3.

15.3 Supply vs Demand Driven Strategies

The scale of change required to achieve compliance, as demonstrated by all strategies reviewed, demonstrates that fundamental change is needed within the energy landscape of the SN region, regardless of the chosen pathway. The two broad categories of decarbonisation strategy were:

1) 'Top-down' supply-driven strategies, these concerned achieving compliance via the supply of energy; and,
2) 'Bottom-up' demand-driven strategies, these concerned achieving compliance via the use of energy.

If a compliance strategy were primarily based on demand-driven policy, the magnitude of demand reduction necessary to achieve compliance would result in the majority of savings needing to be made by domestic consumers, on the basis that a material economic reduction in production and manufacturing within the SN area would be unacceptable. Therefore, the three demand-driven scenarios serve to demonstrate the magnitude of personal ownership required of consumers to achieve compliance through individual choice. By virtue of the modelling methodology employed, all demand-driven scenarios include a high degree of investment in low-carbon electricity and high adoption of EVs. Therefore, the level of lifestyle changes calculated regarding; efficiency investment; energy use behaviour; and home comfort levels, would be further magnified if the ultimate deployment of low-carbon electricity or the 90% adoption of EVs were not materialised. As lifestyle changes are a matter of personal choice, and difficult to influence via regulation, it is deemed unlikely that the scale of change required could be realised and sustained without generous subsidies.

The risk profile of achieving the necessary carbon saving requirements through supply-driven strategies is deemed lower than that of demand-driven strategies given the scale of decarbonisation required. The below table provides a summary comparison of supply vs demand driven compliance strategies.

Table 15-1: Supply vs Demand Driven Strategy Comparison

Comparator	Demand-Driven Strategies	Supply-Driven Strategies
Potential to incentivise action	Subsidy offer	Mandated legislation
Number of stakeholders required to act	High	Low
Decarbonising effect of each action	Low	Medium-High
Consumers ability to express personal preference	High	Low

The features outlined above are exemplified by support mechanisms such as The Renewables Obligation – where targeted regulation mandates action in a way that promotes low-carbon investment. By enacting appropriate policy interventions to incentivise large scale investment in low-carbon energy, material decarbonisation equivalent to aggregating a large population of individual decisions can be achieved. An example of this equivalency is represented in the Multi-Vector scenario where:

1) 0.2 TWh of biomethane capacity was found to have an equivalent decarbonising effect, in 2050, to the replacement of 19,000 gas boilers with ASHPs or installing 58,000 hybrid systems;
2) Therefore, a 1 MW biomethane AD plant, in 2050, could avoid the need for 800 households to replace their gas boilers with ASHPs, or 2,500 hybrid installations.

Supply-driven strategies benefit from inherent economics of scale, relative to demand-driven strategies which rely on aggregating individual decisions where each decision must be financially incentivised. This effect can materialise in generally lower deployment costs for supply-driven solutions. For example, for heat decarbonisation, both biomethane plants and ASHPs can receive a Renewable Heat Incentive (RHI) subsidy. Although the carbon reduction equivalency calculated is for 2050, applying current subsidy prices can provide a basis for cost comparison. The following subsidy comparison is for a 10 MW biomethane plant vs 8,000 ASHPs, given that these have been calculated by the Pathfinder model to provide the same decarbonising effect in 2050.

Example Calculations: 10 MW Biomethane Plant

1) Annual output would be 87,600 MWh pa;
2) Current subsidy would be £43/MWh (based on current pricing tiers[24]);
3) Annual subsidy would therefore be £3.7M pa.

Example Calculations: 8000 ASHPs

1) Annual average heat output would be 12.5 MWh per ASHP (based on average domestic heat use[25]);
2) Assuming an average COP of 3, the subsidised output would be 67% (based on Ofgem guidance[26]);
3) Therefore, total annual subsided output would be 67,000 MWh pa;
4) Current subsidy would be £100/MWh (based on current pricing[27]);
5) Annual subsidy would therefore be £6.7M pa.

Taking the calculated 2050 carbon reduction equivalency between ASHPs and biomethane capacity, the current subsidy cost of a demand-driven ASHP strategy would be 80% greater than the current subsidy cost of a supply-driven biomethane strategy. Alongside the increased support costs, the ASHP strategy would be contingent on 8000 households taking the decision to install an ASHP, compared to the biomethane strategy which would require the construction of one plant.

Given the relative impact of supply-driven compared with demand-driven investment, a compliant strategy would be likely dominated by supply-based vectors, supported by demand-based solutions where necessary. As supply based vectors influence energy use en masse, they are less likely to engage off-grid households. Demand-based vectors may be more appropriate for decarbonising smaller demographic categories such as off-grid homes – where, for example an LPG hybrid ASHP solution would make material savings.

Demand driven vectors do play an important role in a decarbonisation strategy, given the increased magnitude of change required on other vectors if they were excluded. However, it is likely that policy which has a greater focus on supply-driven low-impact solutions, working in conjunction with targeted demand-driven solutions, would yield lower-risk compliance pathways.

15.4 Heat Associated Carbon Emissions

All scenarios demonstrated that meeting the 2050 carbon targets in the SN area can only be achieved by reducing emissions associated with heat demand. This is most clearly shown by the Consumer Led and Business Led scenarios, where even with the assumed level of EV adoption *and* assuming all domestic power consumption were *eliminated*, it was not possible to reach the carbon targets without addressing heat emissions. To achieve compliance, one or more of the three following strategies would need to be deployed:

1) Reduce gas demand, using increased efficiency or lower domestic comfort levels;
2) Reduce the carbon intensity of gas, using biomethane and/or hydrogen;
3) Electrify heat using low-carbon electricity, flexible generation and reinforcement.

Any carbon compliant policy would require adoption of one or more of the above. The combination of the above approaches which results in the lowest-regret pathway would be geographically and demographically specific. However general conclusions can be derived by reviewing the activities required and investment implications of all three, to understand the relative merits of each option.

To reduce gas demand, either comfort levels would have to reduce, or the efficiency of buildings would have to increase. Both of these route maps are predicated on aggregated individual consumer choices; therefore, they are both inherently higher risk given the magnitude of change required for either option to yield material results.

For consumers to lower their heating demand, enduring lifestyle changes would need to be accepted en masse. The primary lifestyle change would be a reduction in home temperatures of up to 6 °C (as per Section 10.2). As the long-term trend of household temperatures is one of an *upward* curve, this would require reversing the trend and sustaining the change. It is deemed unlikely that the majority of consumers would willingly accept a lower standard of comfort in the form of cooler homes, and that any reduction could be sustained in perpetuity by choice.

The second option of increasing home efficiency would require existing home owners to retrofit efficiency measures (both on-grid and off-grid homes, with a split of 83% and 17% respectively[28]) as well as changes to building codes for new homes. Given that retrofitting homes could be promoted via government supported subsidy schemes and new home efficiency could be improved by a change to construction standards, this option of reducing gas demand would likely represent a lower-risk route map relative to attempting to reduce comfort levels. Although the ultimate decarbonisation that could be achieved via increased efficiency is lower than reducing heat demand (given the 28% technical upper limit of home efficiency gains[7]), it would likely be more achievable and is inherently longer term.

Reducing the carbon intensity of gas could be achieved either via investing in biomethane or hydrogen. One of the main advantages of these vectors is the fact they are supply-driven with zero or relatively low impact on consumers.

Biomethane is a direct low-carbon replacement to natural gas that does not require downstream investment and can be produced using domestic feedstocks, and is therefore an important decarbonising vector. The disadvantages of biomethane relate to feedstock supply chains and capacity, as imports would be required to achieve greater capacity than 100 TWh[9].

Hydrogen is a low-carbon replacement to natural gas that requires a greater degree of infrastructural investment relative to biomethane (CCUS & transmission), however it has effectively unlimited feedstock as it can be derived from natural gas. The potential generation capacity of hydrogen is its main advantage in the green gas landscape. If reducing the carbon intensity of gas is a central principle of carbon compliant policy then hydrogen development would likely provide a pathway to deeper decarbonisation beyond biomethane. Given the potential downstream implications, and investment required for hydrogen adoption, a deployment pathway is expected to be lower regrets by minimising disruption to domestic consumers such as through blending, and maximise penetration into high density energy users such as industrial clusters.

Both biomethane and hydrogen are supply-driven solutions that are reliant on policy and regulation, instead of aggregated consumer decisions, to yield material carbon savings. Therefore, both vectors should be considered within an overarching heat strategy as they are likely to be a lower risk strategy to reduce gas emissions, relative to a counterfactual of demand-driven solutions.

The third option to reduce emissions associated with heat is to electrify heat and install low-carbon generation, inclusive of flexible generation to handle intermittency, to provide the primary energy supply. At a consumer level this strategy would result in the installation of ASHPs, either as stand-alone systems or hybrids alongside gas boilers. Much like the installation of energy efficiency measures, adoption could be promoted via government subsidy schemes such as the Renewable Heat Incentive (RHI) or via modification to building regulations. The success of this strategy would be contingent on consumers having ready access to capital, accepting disruption as well as investment in both generation (low-carbon and flexible) and transmission/distribution.

The deployment pathway of electrifying heat could be de-risked by promoting a hybrid solution as such installations are less disruptive to consumers than full replacement systems, and require less investment in both generation and distribution of electricity due to their inherent flexibility. Alongside hybrid solutions, smart hybrid solutions could offer further advantages as, the selection of energy source (electricity vs gas) can be made intelligently based on user specifications.

A material factor regarding any electrification strategy is the impact of EV adoption. The reference point assumed no significant electrification of heat; however, it did assume a

90% adoption rate of EVs and the resulting implications for the electricity network were found to be significant. Therefore, for electrification of heat to play a material role in reducing heat emissions, an investment programme of electricity network reinforcement and low-carbon generation would be required – as detailed in Section 7.4.

Based on the three categories of options and considerations of deployment pathway risk and number of stakeholders affected, a sequential merit order of heat decarbonisation options has been generated. This proposed seriatim takes into account the relative advantages of supply-driven vs demand-driven strategies, whilst accounting for the relative certainty of incentivisation and stakeholders affected.

Figure 14-1: Heat Solutions Seriatim

To achieve compliance within the SN area, a combination of the three options outlined above would need to be reviewed and evaluated by local policy makers to suit the local area. Compliance is more likely to be achieved by adopting policy directions which are reliant on options that are low-disruption to consumers, where regulatory frameworks can directly promote deployment, and where the number of stakeholders required to act is minimised.

15.5 Gas Network Implications

In all the compliant scenarios modelled, there is a level of reduction in both annual and peak gas demand due to the necessity to reduce heat related emissions and improved home efficiency.

The additional installation of flexible generation in the form of gas turbines and engines was common to all scenarios, as low-cost flexible power production was required to supplement intermittent low-carbon generation. Such flexible gas-fired generation can enable a higher penetration of low-carbon intermittent sources and promote deeper decarbonisation of the electricity network. Therefore, it is likely that all GDNs will see an increase in connection requests regardless of macro-decarbonisation strategy. The implications for gas networks therefore relate to storage and peak demand.

Both the average and peak gas demand reduced by 35% relative to today, based on the Pathfinder modelling undertaken. Therefore, the peak demand capacity of the current network supplying the SN would likely be capable of supplying the additional flexible gas-fired generation. However, local network constraints could materialise if flexible gas turbines are installed in a clustered fashion, as the topology of peak demand would shift from being distributed to clustered. Diurnal storage requirements will change, due to the forecast increasing effect on flexible generation capacity due to electric vehicle charging.

Given the reduced load factor forecast for the gas network, efficient operations will be essential to minimise the impacts on consumers bills. Business plans should therefore continue with maintenance and replacement programmes to maximise operational efficiency into the future.

Facilitating flexible demand connections will play an import enabling role in allowing flexible generation to connect to the gas grid and provide necessary generation capacity when required. This flexible functionality will be especially important as the electricity network becomes more reliant on intermittent low-carbon sources and must supply ever more variable demand in the form of electric vehicles.

Despite reducing gas demand, addressing its carbon intensity also remains important. Gas network investment which promote the adoption of biomethane would likely come in the form of operational functionality that allows gas to be pressurised and stored back up the pressure tiers. Gas network investment which promote the adoption of hydrogen would likely come in the form of additional storage and local network monitoring of caloric value to facilitate a variable CV billing regime.

Business plans which support the roll out of biomethane and hydrogen are expected to be more resilient low carbon strategies as they are not reliant on consumer led changes.

15.6 Electricity Network Implications

There is expected to be a requirement for substantial investment programmes to accommodate the adoption of EVs and potential electrification of heat – as detailed in Section 7.4. Given the regulatory/political drivers and relative product maturity of EVs, in comparison to fuel cell transport, it is likely that electrification will be the dominant decarbonising pathway for passenger vehicles. As Figure 6-4 in Section 6.4 demonstrates, the electrification of passenger vehicles will have a material effect on:

1) Overall capacity,
2) Peak demand,
3) Rate of demand change.

The network investment implications of a 'decarbonisation through electrification' philosophy, be it for transport or heat, will need to span both capacity and responsiveness. Additional investment will be required to address grid stability, given the forecast installed capacities of intermittent generation could halve inertia relative to current operation. As recognised in National Grid ESO's 'Zero-carbon operation' report[21].

Aggregating the supply and demand forecasts, the operational and investment implications for the electricity network supplying the SN area will be significant. Therefore, RIIO business plans from now until 2050 are expected to need to include both:

1) Investment to accommodate up to a 70% increase in peak demand; and,
2) Investment to accommodate up to a tripling of maximum rate of demand change alongside a halving of average generation inertia on average.

These figures have been taken from the Electrification scenario, Section 7.4, as they represent the boundary conditions of change, as calculated from the Pathfinder model.

It is important to note the regionality of solutions. Given the diversity of local generation assets and network constraints, the geography of decarbonisation strategy will likely play a material consideration in determining the lowest-cost pathway. An example being the electrification of heat, which will be lower cost in areas with currently constrained low-carbon generation relative to areas without any spare low-carbon generation.

Given the required changes in electricity network operation across all scenarios, investment in local monitoring would also be of value. This would allow a greater degree of profiling to take place to allow network investment to be geographically aligned with changing consumer behaviour. All scenarios indicate a high degree of investment would be required in the electricity network to achieve compliance. Therefore, holistic strategies which allow the gas network to reduce the magnitude of required change in the electricity network – whilst still enabling a decarbonisation pathway to compliance - are likely to be lower-cost and more achievable. Such alignment would need to be realised through RIIO business plans, which currently are not ‘whole system’ and have a 2-year gap between gas networks (GD2 investment starting in 2021) and electricity networks (ED2 investment starting in 2023).

15.7 Network Synergies

It is evident from the scenarios analysed that the overall network implications are significant and will require targeted investment to maintain operational security in a carbon compliant energy market. Most scenarios indicate the greatest required changes are to the electricity network. Therefore, the focus should be on opportunities or synergies with the gas network to reduce the magnitude of electricity network change and investment.

In terms of technological synergies, the two main synergies that have been derived from the Pathfinder modelling are:

1) Investment in low-carbon gas, as this both; reduces the need for ASHP electrification (reducing the variability of demand on the electricity network); and, lowers the carbon intensity of electricity generated from gas-fired generation (reducing the necessity to invest in intermittent generation).
2) Investment in hybrid ASHPs relative to stand-alone ASHPs, where heat electrification is required. Hybrid systems are inherently more flexible and reduce the peak demand requirement of the electricity network, however a ratio of 3:1 was found in the Multi-Vector scenario for hybrid:ASHP installations to achieve the same decarbonisation effect.

In terms of wider synergy options, a development of smart TOUTs to optimise consumer electricity usage and reduce peak demand would yield system benefits. By reducing peak electricity demand:

1) Network investment in peak demand will reduce, an example being the 15% reduction in additional peak demand from optimised EV charging;

2) Investment in flexible generation to supply peak demand will reduce;
3) Greater utilisation of the electricity network can be achieved.

Further synergies which are outside of the scope of this report, include:

1) Integrated demand forecasting to ensure the collective energy system can reliably deliver the forecast mix and variability of demands – with specific implications for gas network diurnal storage;
2) Network connection applicants being visible to both networks, improving demand forecasts and informing future plans;
3) Greater operational integration between network control rooms to promote communication and system-based decision making;
4) An agreed technical assessment tool which incorporates both networks to inform RIIO business plan development.

The challenge of meeting our carbon targets is one which impacts both the gas and electricity networks. Policies and technologies that promote cooperation enable cost reductions and de-risk delivery to the benefit of society at large.

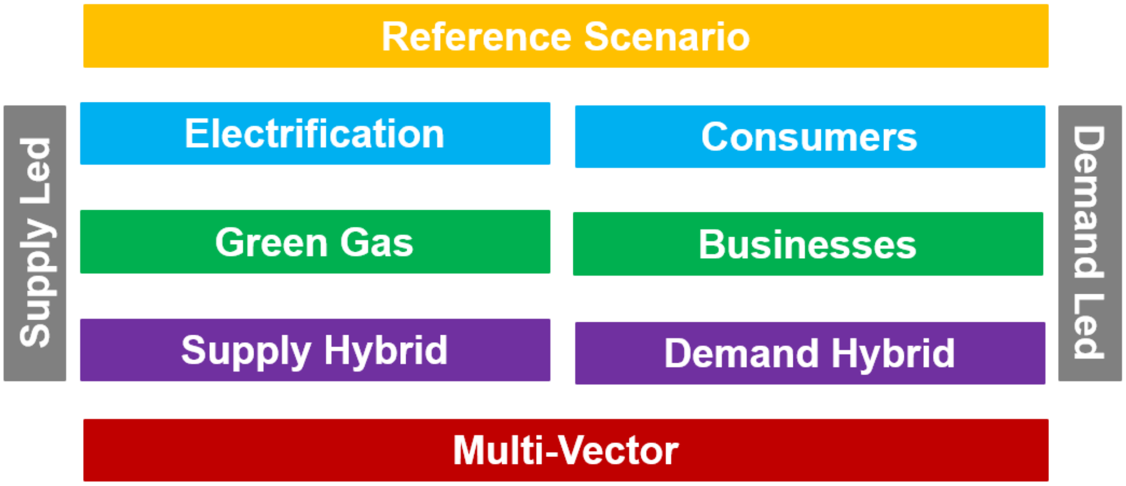
16.0 CONCLUSIONS

16.1 Scenarios Considered

The tool used to undertake the Green City Vision study was the Pathfinder model, developed by WWU and Delta-EE. The Pathfinder model was found to be an incredibly powerful and insightful tool which was capable of providing real insight and system understanding when comparing decarbonisation strategies.

The scenarios considered constituted a technical comparison of top-down 'supply-driven' strategies with bottom-up 'demand-driven' strategies, with incremental hybridisation applied to demonstrate the relative system advantages of holistic decarbonisation strategies. The scenario map used to understand compliance options of the SN region is given below.

Figure 5-1: Scenario Map



The following is a summary of further work which would aid further understanding and insights:

1) Economic assessment of scenarios considered to build upon the technical analysis undertaken within this study;
2) Consideration of other potential decarbonisation strategies, incorporating further sensitivities of the reference scenario;
3) Modelling the pathway to 2050, given that Pathfinder's scope of analysis is an hour-by-hour analysis of one year.

16.2 Energy Users

16.2.1 Consumers

Consumer choice lies at the heart of decarbonisation strategies, as ultimately consumers' energy bills, taxes or personal economy will provide the financial pathway to compliance. The range of potential impacts to consumers' lifestyles and personal finances is very broad, dependent on the structure of any given decarbonisation strategy. Based on the results of the Green City Vision study, the following consumer-orientated general observations can be made:

1) Consumer preferences for funding route of decarbonisation strategies will have a material effect on the ultimate decarbonisation pathway;
2) The suitability and optimality of decarbonisation options is demographic specific – the lowest cost option for one consumer might not be the lowest cost option for another;
3) Decarbonisation strategies relying heavily upon consumers to make individual choices which, when aggregated, result in achieving compliance, are unlikely to be successful, as demonstrated by the Consumer Led scenario which required the ubiquitous installation of every technical home efficiency option and reducing average home temperatures by up to 6 °C to achieve compliance, among other changes.
4) No-regrets focus areas for consumers to contribute to decarbonisation are; the installation of home efficiency measures, where feasible and as personal finances allow; investment in energy efficient appliances; investment in electric transportation; and adjusting lifestyles to reduce peak electricity demand.

16.2.2 Businesses

Businesses are another important category of energy users, whose interests will have a material effect on the ultimate compliance strategy used to achieve compliance within the SN region and nationally. Based on the results of the Green City Vision study, the following business-orientated general observations can be made:

1) Business energy use is intimately licked with economic output and value creation, therefore any decarbonisation strategy that relies upon modifying energy use by businesses should be considered within a wider policy context;
2) Much like consumer-driven strategies, any decarbonisation strategy that relies too heavily on business decarbonisation is unlikely to be successful, given the knock-on effects on economic output. As demonstrated by the Business Led scenario where a reduction in both gas and electricity demand of 45% was required by businesses in the SN region to achieve compliance, among other changes;
3) No-regret focus areas for businesses to contribute to decarbonisation are; electrifying LGVs and converting HGVs to CNG; installation of efficiency measures to reduce heating requirements; upgrading of HVAC systems to provide more efficient heating.

16.3 Energy Networks

16.3.1 General Observations

The general conclusions concerning the utilisation of the gas and electricity networks in achieving compliance within the SN region are summarised below:

1) All compliant scenarios rely upon the continued operation of both the gas and electricity networks. Even when compliance was principally achieved through the use of one network, such as the Electrification and Green Gas scenarios, both networks played an important role in achieving decarbonisation;
2) Achieving carbon reduction compliance will increase the level of integration and interdependencies between the gas and electricity networks. To facilitate this integration and ensure reliable operation of the energy system, integrated demand and constraint forecasting should become part of standard operation;
3) Technologies that leverage the advantageous system characteristics of each network, to enable decarbonisation, should be favoured. Given the forecast implications of electrifying personal transport, harnessing the gas network will likely enable a less disruptive pathway to compliance.

16.3.2 Gas Network

The resulting implications that specifically relate to the gas network supplying the SN region, resulting from the Pathfinder scenario modelling of this project, are summarised below:

1) Both average and peak demand is forecast to reduce by an average of 35% relative to current operation, based on the scenarios modelled, primarily due to forecast improvements in home efficiency;
2) Diurnal storage requirements will become more variable as the daily demand patterns become seasonal. This effect is principally due to the requirements of flexible capacity during the summer when heating demand is low and EVs require charging;
3) Due to forecast reduced load factors, ensuring maintenance and replacement programmes are continued to minimise operational costs, should be a priority;
4) Facilitation of low-carbon gas production, such as; pressure tier recompression for inter-seasonal biomethane storage; and, investment in hydrogen distribution, will ensure necessary optionality is maintained in determining the lowest cost compliance pathway.

16.3.3 Electricity Network

The resulting implications that specifically relate to the electricity network supplying the SN region, resulting from the Pathfinder scenario modelling of this project, are summarised below:

1) Total demand within the SN region is forecast to increase by an average of 50% relative to current operation and peak demand is forecast to increase by 45% on

average, based on the scenarios modelled, primarily due to transport electrification;

2) Operation of the electricity network will become much more dynamic, as measured by rates of change of both supply and demand. Given that the electricity network is forecast to cater for more intermittent demand i.e. EV charging and potentially ASHPs, and will be supplied by a greater proportion of low-carbon intermittent generation i.e. wind and solar;
3) The average generation inertia is due to reduce to 50%, relative to a current average of 70%. Based on Pathfinder modelling of the forecast generation mix, minimum-hour inertia will be 20%. Therefore, development of an inertia service market, such as the one referenced in National Grid ESO's 'Zero carbon operation' report[21] will likely be required to ensure reliable and stable operation;
4) Regional constraint forecasting and management will be an important tool in ensuring investment programmes are tailored to provide additional capacity and functionality where the need arises, on the pathway to compliance.

16.4 Decarbonisation Policy

16.4.1 National Policy

Emissions reduction, by and large, will likely be driven by national policy. Therefore, the following general observations have been derived from the scenario modelling to inform national policy creation:

1) There is no golden solution to achieve compliance, as shown by the Supply-Hybrid, Demand-Hybrid and Multi-Vector scenarios; applying strategies with a range of contributory technologies yield system benefits and reduce investment needs;
2) The decarbonisation of heat is a necessary condition for compliance. Focusing on low-carbon gas, supported by other measures, is seen as the least disruptive pathway to compliance;
3) Due to the magnitude of change necessary to achieve compliance, top-down 'supply-driven' strategies were found to be less disruptive to consumers than bottom-up 'demand-driven' strategies, as demonstrated by the example comparison of biomethane and ASHPs in Section 15.3;
4) Decarbonisation solutions which minimise the number of affected stakeholders and allow deployment pathways to be mandated by regulation, are likely to be more successful than those that rely on the collective good will of many stakeholders, given the magnitude of change required to achieve compliance.

16.4.2 Local Policy

Local policy will remain important in enabling compliance. Therefore, the following observations have been derived from the scenario modelling to inform local policy:

1) The creation of local drivers, such as clean air zones, will create a strong driver for decarbonisation;
2) Facilitating development of low-carbon infrastructure will be vital in ensuring investments can be made to deliver the lowest-cost compliance pathway.

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A.1.0 REFERENCE SCENARIO INPUTS

Pathfinder User Inputs		
Input Parameter	**Value**	**Units**
Population		
Population	562,349	people
Average number of people per household	2.4	people/household
Number of households	234,312	households
Building energy efficiency		
Building energy efficiency improvement in scenario	19%	percentage
Electric vehicles		
Number of electric cars	238,810	cars
Number of electric vans	9,043	vans
Number of electric HGVs	410	HGVs
Gas vehicles		
Number of car/van to fill per day	0	busses
Number of HGVs to fill per day	1,138	HGVs
Domestic heat		
Households with gas heating	69%	percentage
Households with direct electric heating	9%	percentage
Households with electrically powered heat pumps, no backup	6%	percentage
Households with hybrid electricity/gas heat pumps	4%	percentage
Households with hybrid electricity/oil heat pumps	0%	percentage
Households with hybrid electricity/LPG heat pumps	0%	percentage
Households with oil heating	7%	percentage
Households with LPG heating	4%	percentage
Households with biomass heating	2%	percentage
Commercial heat		
Percentage commercial heat supplied by CHP annually	23%	percentage

Pathfinder User Inputs		
Input Parameter	**Value**	**Units**
Electricity supply		
Hydroelectric installed capacity	10	MW
Tidal - Lagoon installed capacity	0	MW
Tidal - Stream installed capacity	5	MW
Tidal - Wave installed capacity	0	MW
Solar installed capacity	137	MW
Wind installed capacity	257	MW
Nuclear installed capacity	76	MW
Geothermal installed capacity	0	MW
Coal installed capacity	0	MW
Coal + CCS installed capacity	0	MW
Oil installed capacity	0	MW
Biomass installed capacity	18	MW
OCGT installed capacity	17	MW
CCGT installed capacity	163	MW
CCGT + CCS installed capacity	34	MW
Electricity 'storage'		
Hydrogen generation capacity	0	MW
Hydrogen storage capacity	0	MWh storage
Commercial battery capacity	387	MWh storage
Green gas		
Green gas supply	7	MW
Green gas storage capacity	120,000	MWh storage
Gas storage capacity utilised at model start	0%	percentage

Pathfinder Fixed Inputs		
Input Parameter	**Value**	**Unit**
Light and power		
Typical domestic light and power consumption without energy efficiency	4,290	kWh/household/year
Domestic % of light and power consumption	75.00%	percentage

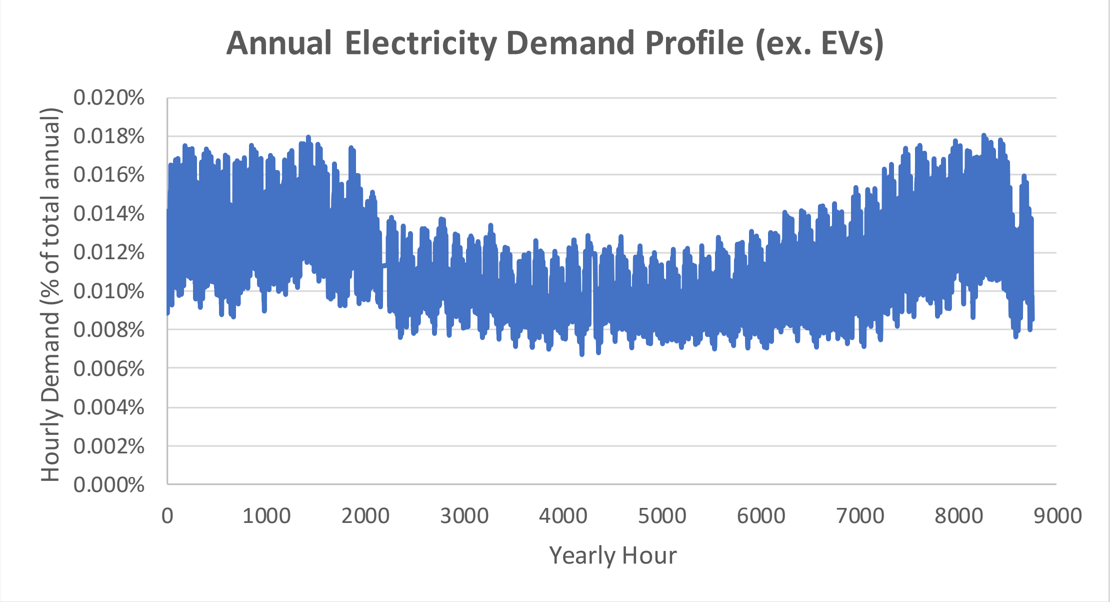
Pathfinder Fixed Inputs		
Input Parameter	**Value**	**Unit**
Commercial and industrial % of light and power consumption	25.00%	percentage
Electric vehicles		
Percentage of electric cars that are unconstrained	48%	percentage
Percentage of electric cars that are constrained	48%	percentage
Percentage of electric cars that are smart	5%	percentage
Percentage of electric vans that are unconstrained	48%	percentage
Percentage of electric vans that are constrained	48%	percentage
Percentage of electric vans that are smart	5%	percentage
Percentage of electric HGVs that are unconstrained	48%	percentage
Percentage of electric HGVs that are constrained	48%	percentage
Percentage of electric HGVs that are smart	5%	percentage
Percentage of electric cars that are unconstrained	48%	percentage
Car electricity consumption	4.7	kWh elec/vehicle/day
Vans electricity consumption	15.4	kWh elec/vehicle/day
HGVs electricity consumption	87.1	kWh elec/vehicle/day
Vehicle battery capacity	32	kWh storage/vehicle
Smart electric vehicles available	80%	percentage
Heat - gas		
Typical domestic gas consumption without energy efficiency	14,700	kWh gas/household/year
Domestic % of gas consumption	65.0%	percentage
Commercial % of gas consumption	35.0%	percentage
Boiler efficiencies:		

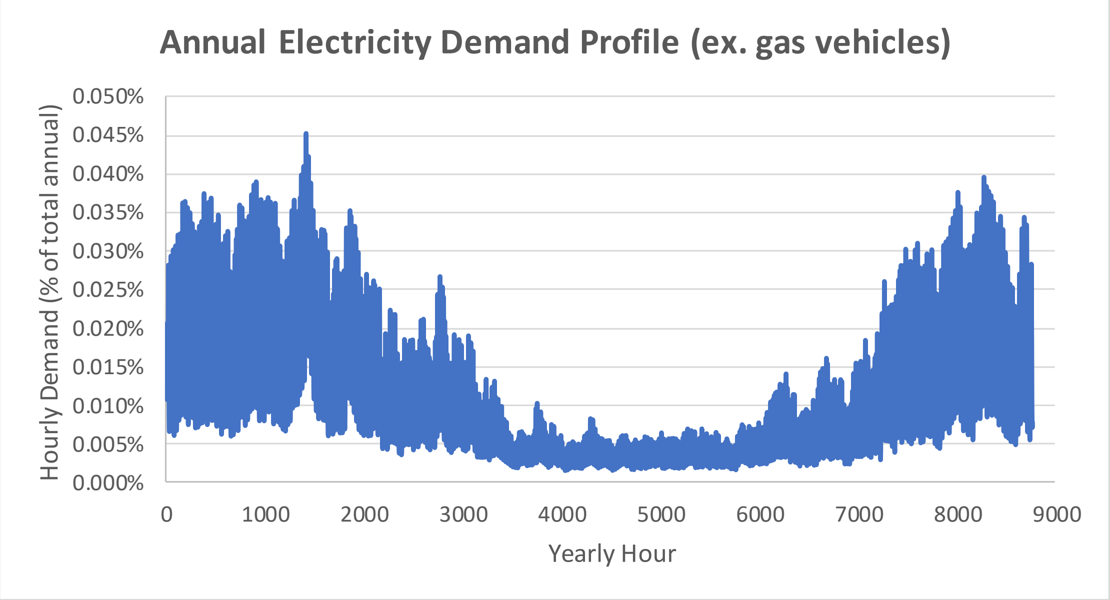
Pathfinder Fixed Inputs		
Input Parameter	**Value**	**Unit**
Domestic gas boiler efficiency	83%	percentage
Commercial gas boiler efficiency	83%	percentage
Domestic oil boiler efficiency	86%	percentage
Domestic LPG boiler efficiency	83%	percentage
Domestic biomass boiler efficiency	85%	percentage
Thermal efficiency factors for CHP		
CHP Gas in	100%	percentage
CHP Average heat out	48%	percentage
CHP Average electricity out	24%	percentage
CHP Total overall efficiency	72%	percentage
CHP Losses	18%	percentage
CHP Heat to power ratio	2.0	(heat generated)/(electricity generated)
Electricity supply - load factors		
Nuclear load factor	77%	percentage
Geothermal load factor	85%	percentage
Electricity supply - transmission and distribution losses		
Transmission and distribution losses	8.28%	percentage
Electricity 'storage'		
Battery storage efficiency	85%	(energy out)/(energy in)
Vehicle battery capacity utilised at model start	0%	percentage
Commercial battery capacity utilised at model start	0%	percentage
Hydrogen storage capacity utilised at model start	0%	percentage
Hydrogen generation efficiency	75%	percentage
Controllable electricity supply merit order		
Coal merit order	8	N/A
Coal + CCS merit order	7	N/A
Oil merit order	6	N/A

Pathfinder Fixed Inputs		
Input Parameter	**Value**	**Unit**
Biomass merit order	1	N/A
OCGT merit order	2	N/A
CCGT merit order	5	N/A
CCGT + CCS merit order	4	N/A
Interconnectors merit order	3	N/A
Thermal efficiency factors for gas power stations		
OCGT thermal efficiency	0.320	(electrical energy)/(heat energy)
CCGT thermal efficiency	0.590	(electrical energy)/(heat energy)
CCGT + CCS thermal efficiency	0.518	(electrical energy)/(heat energy)
Gas vehicles		
Bus gas consumption	70	kWh gas/vehicle/day
HGV gas consumption	224	kWh gas/vehicle/day
Gas shrinkage losses		
Gas shrinkage losses	1%	percentage
Gas storage		
Gas storage capacity utilised at model start	0%	percentage
CO2 emission factors (including transmission and distribution losses for electricity generation)		
Hydroelectric grid emission factor	0.000	tonne CO2/MWh elec
Tidal - Lagoon grid emission factor	0.000	tonne CO2/MWh elec
Tidal - Stream grid emission factor	0.000	tonne CO2/MWh elec
Tidal - Wave grid emission factor	0.000	tonne CO2/MWh elec
Solar grid emission factor	0.000	tonne CO2/MWh elec

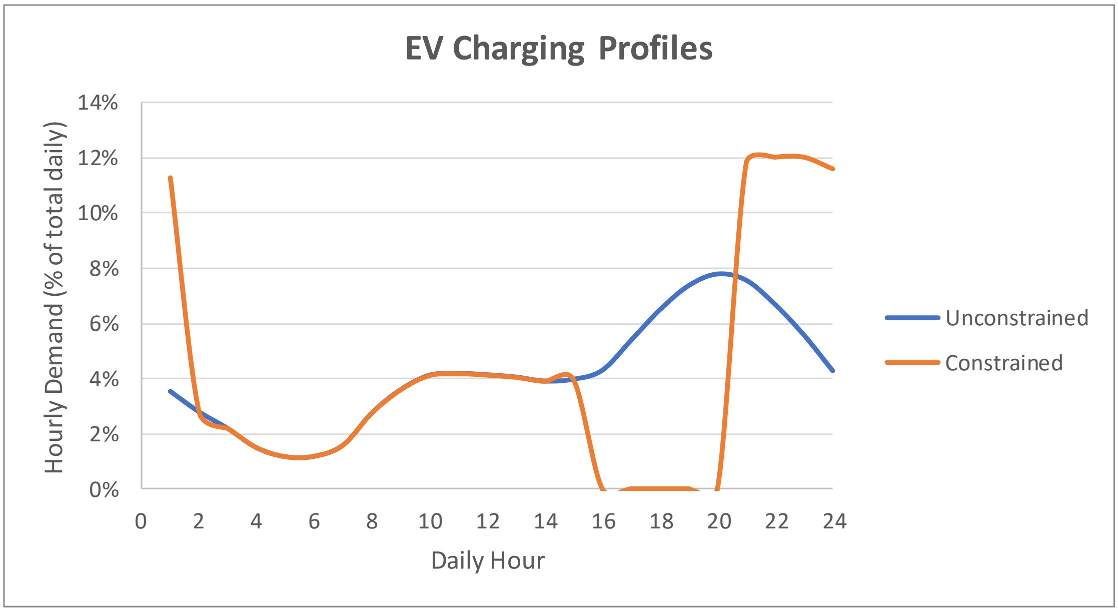
Pathfinder Fixed Inputs		
Input Parameter	**Value**	**Unit**
Wind grid emission factor	0.000	tonne CO2/MWh elec
Nuclear grid emission factor	0.000	tonne CO2/MWh elec
Geothermal grid emission factor	0.000	tonne CO2/MWh elec
Coal grid emission factor	0.970	tonne CO2/MWh elec
Coal + CCS grid emission factor	0.255	tonne CO2/MWh elec
Oil grid emission factor	1.000	tonne CO2/MWh elec
Biomass grid emission factor	0.120	tonne CO2/MWh elec
OCGT grid emission factor	0.820	tonne CO2/MWh elec
CCGT grid emission factor	0.410	tonne CO2/MWh elec
CCGT + CCS grid emission factor	0.210	tonne CO2/MWh elec
Interconnectors grid emission factor	0.090	tonne CO2/MWh elec
Heat Generation		
Natural gas fuel emission factor	0.18400	tonne CO2/MWh (Gross CV)
Green gas fuel emission factor	0.00023	tonne CO2/MWh (Gross CV)
Hydrogen fuel emission factor	0.00000	tonne CO2/MWh (Gross CV)
Oil fuel emission factor	0.24659	tonne CO2/MWh (Gross CV)
LPG fuel emission factor	0.21451	tonne CO2/MWh (Gross CV)
Biomass fuel emission factor	0.01270	tonne CO2/MWh (Gross CV)

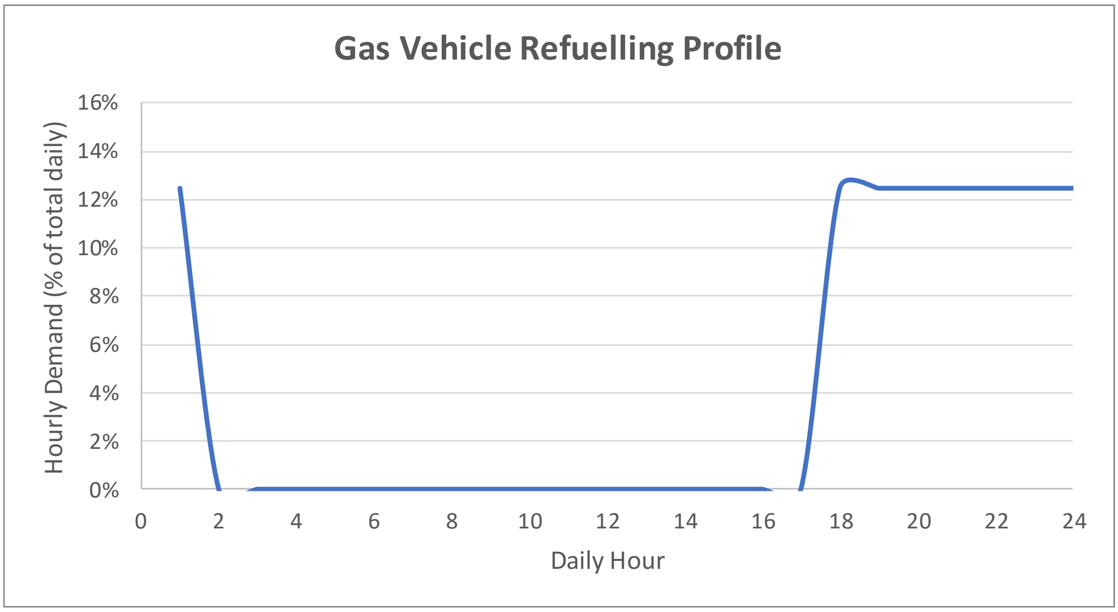
Key demand profiles within the Pathfinder model:





Vehicle charging/refuelling profiles within the Pathfinder model:





A.2.0 ELECTRIFICATION SCENARIO INPUTS

Modelling parameter values which differ from the reference scenario are listed below.

Pathfinder User Inputs		
Input Parameter	**Value**	**Units**
Electric vehicles		
Number of electric cars	238,810	cars
Number of electric vans	29,117	vans
Number of electric HGVs	821	HGVs
Domestic heat		
Households with gas heating	36%	percentage
Households with direct electric heating	9%	percentage
Households with electrically powered heat pumps, no backup	26%	percentage
Households with hybrid electricity/gas heat pumps	16%	percentage
Households with hybrid electricity/oil heat pumps	0%	percentage
Households with hybrid electricity/LPG heat pumps	0%	percentage
Households with oil heating	7%	percentage
Households with LPG heating	4%	percentage
Households with biomass heating	2%	percentage
Electricity supply		
Hydroelectric installed capacity	10	MW
Tidal - Lagoon installed capacity	0	MW
Tidal - Stream installed capacity	5	MW
Tidal - Wave installed capacity	0	MW
Solar installed capacity	218	MW
Wind installed capacity	411	MW
Nuclear installed capacity	122	MW
Geothermal installed capacity	0	MW
Coal installed capacity	0	MW
Coal + CCS installed capacity	0	MW

Pathfinder User Inputs		
Input Parameter	**Value**	**Units**
Oil installed capacity	0	MW
Biomass installed capacity	18	MW
OCGT installed capacity	17	MW
CCGT installed capacity	163	MW
CCGT + CCS installed capacity	34	MW

Pathfinder Fixed Inputs		
Input Parameter	**Value**	**Unit**
Electric vehicles		
Percentage of electric cars that are unconstrained	53%	percentage
Percentage of electric cars that are constrained	42%	percentage
Percentage of electric cars that are smart	5%	percentage
Percentage of electric vans that are unconstrained	53%	percentage
Percentage of electric vans that are constrained	42%	percentage
Percentage of electric vans that are smart	5%	percentage
Percentage of electric HGVs that are unconstrained	48%	percentage
Percentage of electric HGVs that are constrained	48%	percentage
Percentage of electric HGVs that are smart	5%	percentage
Percentage of electric cars that are unconstrained	53%	percentage

A.3.0 GREEN GAS SCENARIO INPUTS

Modelling parameter values which differ from the reference scenario are listed below.

Pathfinder Fixed Inputs		
Input Parameter	**Value**	**Unit**
CO2 emission factors (including transmission and distribution losses for electricity generation)		
OCGT grid emission factor	0.395	tonne CO2/MWh elec
CCGT grid emission factor	0.197	tonne CO2/MWh elec
CCGT + CCS grid emission factor	0.101	tonne CO2/MWh elec
Heat Generation		
Natural gas fuel emission factor	0.089	tonne CO2/MWh (Gross CV)

A.4.0 SUPPLY HYBRID SCENARIO INPUTS

Modelling parameter values which differ from the reference scenario are listed below.

Pathfinder User Inputs		
Input Parameter	**Value**	**Units**
Domestic heat		
Households with gas heating	44%	percentage
Households with direct electric heating	9%	percentage
Households with electrically powered heat pumps, no backup	23%	percentage
Households with hybrid electricity/gas heat pumps	11%	percentage
Households with hybrid electricity/oil heat pumps	0%	percentage
Households with hybrid electricity/LPG heat pumps	0%	percentage
Households with oil heating	7%	percentage
Households with LPG heating	4%	percentage
Households with biomass heating	2%	percentage
Electricity supply		
Hydroelectric installed capacity	10	MW
Tidal - Lagoon installed capacity	0	MW
Tidal - Stream installed capacity	5	MW
Tidal - Wave installed capacity	0	MW
Solar installed capacity	137	MW
Wind installed capacity	257	MW
Nuclear installed capacity	76	MW
Geothermal installed capacity	0	MW
Coal installed capacity	0	MW
Coal + CCS installed capacity	0	MW
Oil installed capacity	0	MW
Biomass installed capacity	18	MW
OCGT installed capacity	17	MW

Pathfinder User Inputs		
Input Parameter	**Value**	**Units**
CCGT installed capacity	163	MW
CCGT + CCS installed capacity	34	MW

Pathfinder Fixed Inputs		
Input Parameter	**Value**	**Unit**
CO2 emission factors (including transmission and distribution losses for electricity generation)		
OCGT grid emission factor	0.555	tonne CO2/MWh elec
CCGT grid emission factor	0.278	tonne CO2/MWh elec
CCGT + CCS grid emission factor	0.142	tonne CO2/MWh elec
Heat Generation		
Natural gas fuel emission factor	0.125	tonne CO2/MWh (Gross CV)

A.5.0 CONSUMER LED SCENARIO INPUTS

Modelling parameter values which differ from the reference scenario are listed below.

Pathfinder User Inputs		
Input Parameter	**Value**	**Units**
Building energy efficiency		
Building energy efficiency improvement in scenario	28%	percentage
Electric vehicles		
Number of electric cars	238,867	cars
Number of electric vans	19,614	vans
Number of electric HGVs	410	HGVs

Pathfinder Fixed Inputs		
Input Parameter	**Value**	**Unit**
Light and power		
Typical domestic light and power consumption without energy efficiency	2,574	kWh/household/year
Heat - gas		
Typical domestic gas consumption without energy efficiency	8,820	kWh gas/household/year

A.6.0 BUSINESS LED SCENARIO INPUTS

Modelling parameter values which differ from the reference scenario are listed below.

Pathfinder User Inputs		
Input Parameter	**Value**	**Units**
Building energy efficiency		
Building energy efficiency improvement in scenario	28%	percentage
Electric vehicles		
Number of electric cars	238,867	cars
Number of electric vans	18,529	vans
Number of electric HGVs	1,210	HGVs
Gas vehicles		
Number of HGVs to fill per day	3,355	HGVs
Commercial heat		
Percentage commercial heat supplied by CHP annually	46%	percentage

Pathfinder Fixed Inputs		
Input Parameter	**Value**	**Unit**
Light and power		
Typical domestic light and power consumption without energy efficiency	2,360	kWh/household/year
Heat - gas		
Typical domestic gas consumption without energy efficiency	8,085	kWh gas/household/year

A.7.0 DEMAND HYBRID SCENARIO INPUTS

Modelling parameter values which differ from the reference scenario are listed below.

Pathfinder User Inputs		
Input Parameter	**Value**	**Units**
Building energy efficiency		
Building energy efficiency improvement in scenario	24%	percentage
Electric vehicles		
Number of electric cars	238,810	cars
Number of electric vans	14,558	vans
Number of electric HGVs	810	HGVs
Gas vehicles		
Number of HGVs to fill per day	2,246	HGVs
Commercial heat		
Percentage commercial heat supplied by CHP annually	35%	percentage

Pathfinder Fixed Inputs		
Input Parameter	**Value**	**Unit**
Light and power		
Typical domestic light and power consumption without energy efficiency	3,218	kWh/household/year
Heat - gas		
Typical domestic gas consumption without energy efficiency	11,025	kWh gas/household/year

A.8.0 MULTI-VECTOR SCENARIO INPUTS

Modelling parameter values which differ from the reference scenario are listed below.

Pathfinder User Inputs		
Input Parameter	**Value**	**Units**
Electric vehicles		
Number of electric cars	238,867	cars
Number of electric vans	29,117	vans
Number of electric HGVs	410	HGVs
Gas vehicles		
Number of HGVs to fill per day	2,275	HGVs
Domestic heat		
Households with gas heating	59%	percentage
Households with direct electric heating	9%	percentage
Households with electrically powered heat pumps, no backup	6%	percentage
Households with hybrid electricity/gas heat pumps	14%	percentage
Households with hybrid electricity/oil heat pumps	0%	percentage
Households with hybrid electricity/LPG heat pumps	0%	percentage
Households with oil heating	7%	percentage
Households with LPG heating	4%	percentage
Households with biomass heating	2%	percentage
Electricity supply		
Hydroelectric installed capacity	10	MW
Tidal - Lagoon installed capacity	0	MW
Tidal - Stream installed capacity	5	MW
Tidal - Wave installed capacity	0	MW
Solar installed capacity	147	MW
Wind installed capacity	276	MW
Nuclear installed capacity	82	MW
Geothermal installed capacity	0	MW

Pathfinder User Inputs		
Input Parameter	**Value**	**Units**
Coal installed capacity	0	MW
Coal + CCS installed capacity	0	MW
Oil installed capacity	0	MW
Biomass installed capacity	18	MW
OCGT installed capacity	17	MW
CCGT installed capacity	163	MW
CCGT + CCS installed capacity	34	MW

Pathfinder Fixed Inputs		
Input Parameter	**Value**	**Unit**
Heat - gas		
Typical domestic gas consumption without energy efficiency	13,230	kWh gas/household/year
CO2 emission factors (including transmission and distribution losses for electricity generation)		
OCGT grid emission factor	0.566	tonne CO2/MWh elec
CCGT grid emission factor	0.283	tonne CO2/MWh elec
CCGT + CCS grid emission factor	0.145	tonne CO2/MWh elec
Heat Generation		
Natural gas fuel emission factor	0.127	tonne CO2/MWh (Gross CV)