

Technical Feasibility of Electric Heating in Rural Off-Gas Grid Dwellings

Final report

December 2018

Report authors:

Matthew.myers@delta-ee.com

+44 (0)1223 781607

Andrew.turton@delta-ee.com

Erica.marshallcross@delta-ee.com

Laura.glover@delta-ee.com

BEIS Research Series Number 0024



Executive summary

Heating for rural off-gas grid dwellings tends to rely on higher carbon and higher cost fossil fuel sources such as oil and liquified petroleum gas (LPG). BEIS has an ambition to phase out the installation of high carbon fossil fuel heating in new and existing off-gas grid residential buildings during the 2020s, replacing them with lower carbon sources. Electric heating is one major option and includes technologies such as low and high temperature air source and ground source heat pumps, direct electric heating and storage heaters – the technologies investigated in this report.

This report presents an estimation of the number of rural off-gas grid houses that could have electric heating systems installed, considering technical feasibility at a dwelling level and at the level of the local electricity network. The suitability of electric heating technologies at the dwelling level has been tested by considering thermal and electrical constraints. The effects of adding additional insulation measures to the dwellings has also been explored. Practical constraints regarding the installation of electrical heating (e.g. space, noise, aesthetics) have been included separately. The implications of electric heating in rural areas on the low voltage network has been tested by considering the limitations of the low voltage distribution network based on distribution network data.

The suitability of electric heating systems for off gas grid homes are evaluated using an Excel based model with inputs from the Cambridge Housing Model, the most recent English Housing Survey and Living in Wales survey data. The low voltage network constraints are also evaluated using an Excel based model. This model makes use of network data supplied by distribution network operators based in England and Wales, including customer numbers, transformer maximum demand reading data and heating technology specific load profiles.

The results from this analysis indicate a large proportion of dwellings (91%) are technically suitable for electric heating at the dwelling level, with improvements to dwelling insulation levels further increasing the proportion of homes that could be electrified to 97% of rural off-gas grid homes. Heat pumps can enable large energy savings as compared to the incumbent system, whereas direct electric heating systems save very little. It is likely that improvements to a dwelling's heating distribution system will be required in almost all cases if higher efficiency (low temperature, 40°C flow temperature) heat pumps are installed, whereas less than a quarter of heat distribution system will require upgrading for use with high temperature heat pumps (55°C flow temperature). The biggest barrier to the uptake of electric heating for low temperature heat pumps is ensuring a satisfactory level of comfort can be achieved. For high temperature heat pumps, the biggest barrier is achieving a sufficiently high coefficient of performance such that the electrical demand does not exceed the maximum allowable current draw for a dwelling. For all types of electrical heating system, the number of suitable houses decreases when practical limitations are included, but due to the diversity of systems considered, the total number of houses suitable for any one type of electrical heating system remains high (86% at existing insulation levels and 95% if dwellings upgrade their loft and wall insulation).

The results from the network modelling show that based on average peak winter day temperatures, around 84% of homes can be electrified at their current level of insulation. This increases to around 93% if all suitable homes have loft & wall insulation installed. However, based on a 1-in-20 winter peak scenario, the proportion of homes that the current low voltage network can support drops to around 64% if ground-source heat pumps are the preferred technology for households, or to 41% if air-source heat pumps are the preferred technology (assuming that air source heat pumps require a direct electric heating back-up in a 1-in-20 winter scenario). For both merit order scenarios, adding loft and wall insulation results in only a marginal improvement in electrification rates.

Several options are available to reduce the peak demand due to electric heating on the low voltage network. These include improving the efficiency of heat pumps, increasing heat pump capacity to meet the 1-in-20 peak load without the need for additional direct electric heating, or optimised operation to reduce heat pump cycling and peak shifting using smart controls and/or thermal stores or

battery storage. Widespread adoption of such options could result in up to an extra 20% of homes being able to be electrified based on the constraints of the low voltage network.

Table of contents

Executive summary.....	2
Table of contents.....	4
List of acronyms	6
1 Introduction	7
2 Research scope & approach	8
2.1 Project scope.....	8
2.2 Approach.....	8
3 Electric heating system suitability modelling methodology.....	10
3.1 Model structure.....	10
3.2 Model inputs	12
3.3 Sensitivity testing	16
4 Network impacts modelling approach and assumptions	18
4.1 Model structure.....	18
4.2 Model inputs	19
4.3 Limitations	22
4.4 Options available to accommodate additional electric heating load on the low voltage network	22
5 Electric heating system suitability results	24
5.1 Technical feasibility of electric heating systems	24
5.2 Technical feasibility of electric heating systems following energy efficiency improvements	24
5.3 Level of energy savings that can be achieved by electric heating systems	25
5.4 Sensitivity testing	27
5.5 Major barriers to the technical and practical feasibility of electric heating	30
5.6 Application of the merit order to determine installed technology base	31
5.7 Homes requiring an upgrade to their heating distribution system.....	32
6 Network impact of electrification of off gas grid heating	35
6.1 Limitation of the low voltage electricity network to the adoption of electric heating.....	35
6.2 Sensitivity testing	40
6.3 Options available to accommodate additional electric heating	41
7 Conclusions	44
7.1 Heating systems suitability	44
7.2 Network impact of electrification of off gas grid heating	45
Acknowledgements	46

8 Appendix A – heating system suitability	47
8.1 Archetypes used	47
8.2 Scaling housing data to 2016 figures	51
8.3 Heat pump electrical requirements	54
8.4 U-values for Insulation	56
8.5 Practical suitability of electric heating	56
9 Appendix B – network modelling	58
9.1 DNO data cleaning and further assumptions	58
9.2 Calculation of the increase in peak load per dwelling	58
9.3 Major assumptions regarding the network modelling	59
9.4 Load profiles.....	62
9.5 Temperature scenarios	63

List of acronyms

Acronym / abbreviation	Definition
ADMd	After Diversity Maximum Demand
ASHP	Air source heat pump
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEIS	Department for Business, Energy and Industrial Strategy
CIBSE	Chartered Institute of Building Services Engineers
CHM	Cambridge Housing Model
COP	Coefficient of performance
CSA	Cross sectional area (referring to cables)
DNO	Distribution network operator
EHS	English Housing Survey
ENWL	Electricity North West Limited
EV	Electric vehicle
GSHP	Ground source heat pump
HP	Heat pump
HT	High temperature
IWEC	International Weather for Energy Calculations
kVA	Kilo Volt Amperes
LiW	Living in Wales (housing survey)
LT	Low temperature
LPG	Liquefied petroleum gas (bottled)
LV	Low voltage
MCS	Microgeneration Certification Scheme
NEED	National Energy Efficiency Data (Framework)
NPG	Northern Powergrid
RHI	Renewable Heat Incentive
RHPP	Renewable Heat Premium Payment Scheme
SPF	Seasonal Performance Factor
SSE	Scottish and Southern Electricity Networks
UKPN	UK Power Networks
WPD	Western Power Distribution

1 Introduction

Heating for rural off-gas grid dwellings tends to rely on higher carbon and higher cost fossil fuel sources such as oil and liquified petroleum gas (LPG). Consumers are also more vulnerable, having less of the regulatory protection associated with gas and electricity suppliers.

BEIS have an ambition to phase out the installation of high carbon fossil fuel heating in new and existing off-gas grid residential buildings during the 2020s, replacing them with lower carbon sources. Electric heating is one potential option and includes technologies such as low and high temperature air source and ground source heat pumps, direct electric heating and storage heaters.

Building on preliminary analysis conducted by BEIS, this study provides BEIS with robust data and insights on the number of dwellings in rural off-gas grid England and Wales where it is technically feasible¹ to install different types of electric heating, whilst ensuring electricity distribution networks are capable of meeting the increased demands. The outputs will help BEIS formulate future policy and strategy around decarbonisation of rural off-gas grid dwellings so that the most appropriate technologies can be deployed which provide both customer and energy system benefits.

BEIS set out a number of detailed research questions for this study aimed at informing future strategy. Based on these research questions, this study:

- Provides a detailed assessment of the **current technical potential** for different electric heating technologies in rural off-gas grid housing typologies, considering existing efficiency levels, technology suitability and network capacity.
- Identifies how this **current technical potential can be improved by making thermal upgrades** to different housing types to enable the installation of different electric heating technologies.
- Characterises the major barriers to the **technical feasibility** of adopting electric heating.
- Identifies the need to **upgrade heating distribution systems** to enable the integration of electric heating technologies.
- Provides an understanding of the **potential energy saving benefits** which can be obtained from electric heating technologies under the current and thermal upgrade scenarios considering a number of different assumptions.
- Develops an **understanding of the electricity network impacts** based on the technical potential for heating systems to be fitted into off gas grid homes. The opportunities for mitigating reinforcement are also considered.

The answers to these questions will provide the evidence for future analysis of the costs and impacts of different electric heating scenarios.

¹ Considering the thermal comfort of the occupants and the electrical requirements of the electric heating technology

2 Research scope & approach

2.1 Project scope

The scope of this report is limited to the investigation of rural off-gas grid dwellings in England and Wales. The electric heating technologies investigated were limited to: low-temperature air source heat pumps (LT-ASHP), low-temperature ground source heat pumps (LT-GSHP), high-temperature air source heat pumps (HT-ASHP), high-temperature ground source heat pumps (HT-GSHP)², direct electric heating and storage heaters. Hybrid heat pumps and heat pumps where air is the delivery medium were excluded.

Only space heating requirements were considered. While the heat pump technologies mentioned above are in most cases installed to provide space heating and domestic hot water, the heating of domestic hot water was not evaluated in this study. In most cases domestic hot water heating can be scheduled to avoid times of maximum grid loading and are not influenced by wall and loft insulation.

This report focusses on the technical viability of domestic electric heating under different assumptions, but clearly any further policy development in this area will need to consider the economic viability and impacts of the different electric heating approaches and non-electrical low carbon alternatives. Quantitative cost or economic assessment of technologies and approaches is outside the scope of this study.

2.2 Approach

A three-step approach was used to answer all the necessary research questions; data gathering, heating system suitability modelling, and network impacts modelling.

Step 1: Data collection

In order to support the analysis and modelling, a range of datasets were collected including:

- 2015 – 2016 English Housing Survey (EHS) and 2008 Living in Wales (LiW) datasets.
- Distribution network data. We entered into discussions with distribution network operators (DNOs) to obtain data from a number of substations. In an attempt to get good geographic coverage, a number of DNOs were contacted, including: UK Power Networks (UKPN), Western Power Distribution (WPD), Electricity North West limited (ENWL), Northern Powergrid (NPG) and Scottish and Southern Electricity Networks (SSE).
- Electric heating technology datasets. This will include:
 - information on capacities, efficiencies, and seasonal performance factors
 - information and assumptions around technology applicability
 - typical load profiles and operation regimes
 - information on smart controls and flexibility capability.
- Domestic electric load profiles from Elexon

Step 2: Determining the suitability of electric heating systems to off gas grid houses

An Excel model was used to assess the technical and practical suitability of electric heating systems in the off-gas grid housing stock. The electric heating system suitability model is based on inputs from the Cambridge Housing Model (CHM)³ along with a number of technology specific assumptions. The

² Low temperature is defined as a flow temperature of 40°C. High Temperature is defined as a flow temperature of 55°C. Further justification is provided in Section 3.

³ Further information about the CHM is available on the BEIS website - <https://www.gov.uk/government/publications/cambridge-housing-model-and-user-guide> [accessed 27/08/2018]. Version 3.02 of the CHM was used in this work.

model outputs, in addition to answering the research questions listed below, also provide inputs to the network impacts model. The model structure, inputs and the sensitivity analysis performed are further described in Section 3.

The model was used in answering four of the research questions posed by BEIS:

- How many dwellings in off-gas grid areas can technically⁴ have an electric heating system installed in their current state and under what assumptions?
- How many additional dwellings in the off-gas grid can technically have an electric heating system installed following insulation installation (four insulation scenarios)?
 - Loft insulation (virgin and top-up)
 - Loft insulation & floor insulation
 - Loft insulation & cavity wall insulation
 - Loft insulation & solid wall insulation (internal and external)
- What level of energy saving can be expected for different assumption sets used compared to the incumbent heating system?
- What are the major barriers to the technical feasibility of electric heating?

The following research question was answered based on a combination of the model output, primary research interviews with installers and internal Delta-ee expertise:

- What proportion of the off-gas grid housing stock are likely to require an upgrade to their heating distribution system?

The above research questions are directly addressed in Section 5 of the report.

Step 3: Determining the network impact of electrification of off-gas grid heating

An Excel based model was created to assess the low voltage (LV) network impacts of electrifying off gas grid heating. The model was developed based on maximum demand indicator data received from the different distribution network operators (DNOs) in the UK. The model structure, inputs and the sensitivity analysis performed are further described in Section 4. The network impact model was developed to answer two of the research questions provided by BEIS

- What are the limitations from the low voltage electricity distribution network?
- What options are available to accommodate additional electrification of heating by enhancing capability of the low voltage electricity distribution network?

The above research questions are directly addressed in Section 6 of the report - Network impact of electrification of off gas grid heating.

⁴ Considering the comfort of the occupants and the electrical requirements of the heat pump – as per the BEIS Invitation to Tender document TRN (1520/06/2018).

3 Electric heating system suitability modelling methodology

This section of the report describes the overall structure, inputs and sensitives of the electric heating system suitability model. Further justification and detail regarding the model input and assumptions can be found in Appendix A.

3.1 Model structure

This section gives an overview of the model structure. More detail is given in the following section (Section 3.2).

The model is an Excel based model that makes use of linear equations to derive the number of dwellings suitable for electric heating systems, the percentage of houses suitable to each electric heating system and the energy savings of an electric heating system compared to the incumbent.

The initial modelling uses the Cambridge Housing Model (CHM) to calculate dwelling heat loss and annual space heating demand for a representative subset of houses. The CHM contains detailed data from almost 15,000 house samples (taken from the 2011 English Housing Survey (EHS)) which is coupled to a Standard Assessment Procedure (SAP)-based⁵ energy calculator. For each house in the CHM, a weighting factor is included to estimate the number of houses across England which are represented by that sample house. In order that this project represents an up to date analysis of houses across England and Wales, the housing stock information has been updated based on the 2016 EHS data and the Living in Wales survey data. The CHM parameters (e.g. proportion double glazed) were compared to the latest housing stock information and values were altered as necessary. Any non-rural houses with a gas grid connection have been removed from the CHM. More information on this process is given in Appendix A (section 8.2).

From this updated version of the CHM, the following outputs have been calculated for the existing insulation levels and for the three improved insulation levels:

- Dwelling heat loss [W/°C], and
- Annual space heating demand [kWh/yr]

From these inputs, the model calculates the dwelling heat loss at minimum winter temperatures (as defined in the MCS heat pump guidance⁶) and the peak electrical demand for the different electric heating systems for each house in the CHM. The heating requirements for domestic hot water are not in scope of this work. The model uses COP values (taken from literature) to convert the heat demand to an electrical demand.

The model then calculates the technical suitability of each electrical heating system, for each house in the CHM, considering the thermal comfort of occupants (based on indicators taken from the MCS heat emitter guide) and the electrical limit of the household.

⁵ The Standard Assessment Procedure (SAP) is the methodology used by the Government to assess and compare the energy and environmental performance of dwellings. Further information can be found on the following website: <https://www.gov.uk/guidance/standard-assessment-procedure> [accessed 16/10/2018].

⁶ The Microgeneration Certification Scheme (MCS) is an internationally recognised quality assurance scheme supported by the Department for Business, Energy & Industrial Strategy (BEIS). MCS certifies both products and installation companies to help ensure that Microgeneration products are installed to a high standard. It is a requirement of the Domestic Renewable Heat Incentive (RHI) scheme that all heating systems are certified by MCS.

These results are then combined to show the number of each housing archetype which are suitable for each electrical heating system. These results are also shown including practical feasibility, which considers additional factors limiting uptake of the different technologies.

Following the consideration of both the technical and practical feasibility factors, in many cases, houses are still suitable to more than one electric heating technology. In order to calculate the inputs to the low voltage network impacts model (discussed further in Section 4), the heating system suitability model assesses the electrical heating system each CHM sample house would adopt based on a specified order of preference (merit order). These results are then grouped by house archetype, and further consolidated down to house groupings based on house type and level of thermal demand (above ("high") or below ("low") median thermal demand for each house type across all insulation levels). The average installed capacity of electrical heating system is also calculated for each house grouping.

Finally, the model calculates the energy savings for each electrical heating system, compared to the incumbent system, using the annual space heating demand figures and seasonal performance factor (SPF) values taken from literature. The electricity demand for each CHM house is compared to the incumbent energy demand for space heating to calculate the energy savings. These energy savings are then combined into averages per archetype (repeated for different levels of thermal insulation).

The model structure is illustrated in Figure 1 below.

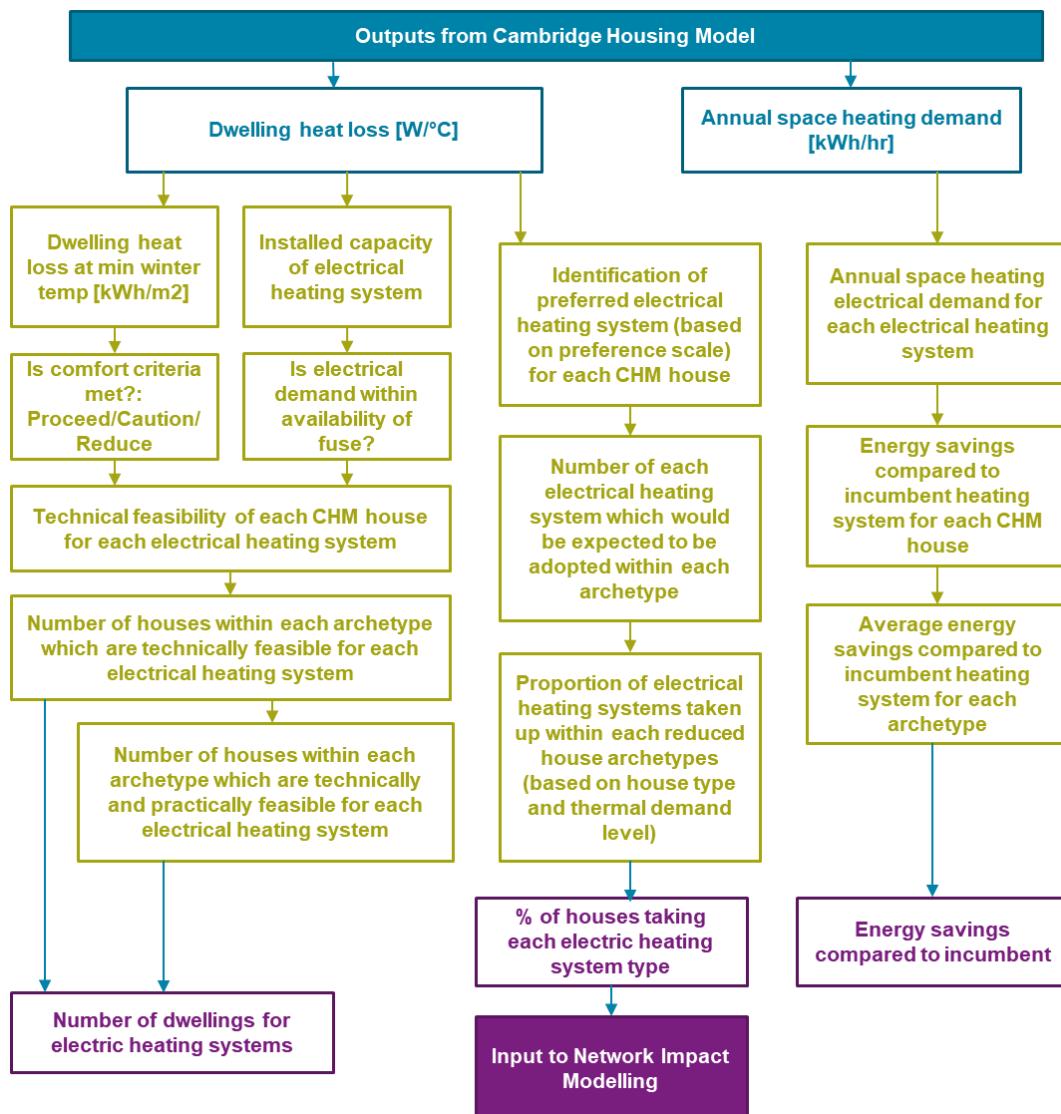


Figure 1: Electric heating system suitability model map

3.2 Model inputs

The model makes use of several inputs based on various sources and assumptions. A list of all assumptions and inputs can be found in the model itself. The sections below describe some of the key model inputs.

Archetypes used in the model

Splitting the housing stock into different archetypes provides a mechanism to identify types of houses that are technically suitable (based on calculated heat loss versus thermal comfort considerations) for different electric heating technologies. In addition, archetypes also allow for a better understanding of the practical feasibility regarding the use of different heating technologies (discussed further below). The archetype breakdown is detailed in Section 8.1.

Housing stock data

The model makes use of both English Housing Survey and Living in Wales housing stock data which had to be updated in the CHM such that the outputs reflect the most up to date building stock across England and Wales (more detail in Section 8.3).

Modelling electrical heating systems

The heat loss of each dwelling ($\text{W}/\text{°C}$) is calculated in the CHM based on the surface area of the dwelling and the U-value of these external surfaces (walls, roof, floor, windows). The CHM also considers factors such as solar gains, internal gains, ventilation and thermal bridging. The rate of heat loss of the dwelling at peak winter is calculated assuming a mean temperature of 19 °C across all rooms of the house (this value can be adjusted in the electric heating system model) and a minimal winter external temperature (values for this are taken from the MCS Heat Emitter Guide⁷).

The electrical demand of the heating system is modelled by assuming that thermal output of the heating system is equivalent to the heat loss for all heating types. A heating efficiency is derived for each heating system type (as further described below) to calculate electrical demand based on the thermal output of the heating system.

A low temperature heat pump is defined as having a flow temperature of 40°C. A high temperature heat pump is defined as having a flow temperature of 55°C⁸. These temperatures are used to assess whether a suitable level of comfort can be delivered within a house (based on the MCS heat emitter guide as described below). Values for the efficiency of heat pumps are derived separately for low and high temperature heat pumps (as described below).

The modelling of storage heating differs to that of direct electric heating by assuming there is a greater availability of current (Amperes/phase) for storage heating as the electricity is drawn at off-peak times when there is less electricity demand from other appliances in the home.

Assessing the thermal comfort of dwellings

The MCS heat emitter guide (MCS 021⁹) was used to assess if a heat emitter (supplied by a heat pump) is able to achieve an acceptable level of thermal comfort. The guide is incorporated into the latest MIS3005 (Heat Pump Standard¹⁰) and provides a basic look-up table to check whether a heat emitter, operating at a given temperature, delivering heat to a room with a certain heat loss (in W/m^2 floor area) will be deemed thermally comfortable to occupants. The levels provided in the guide are as follows:

- **Proceed:** system can perform with the current heat emitters and insulation levels

⁷ DECC (2014), MCS Heat Emitter Guide For Domestic Heat Pumps, Issue 2.1
https://www.microgenerationcertification.org/images/MCS_021_Issue_2.1.pdf [accessed 20/07/2018].

⁸ The reason for this was twofold, first there is better availability for high temperature systems defined as 55°C. Secondly, this definition is as per the following BEIS report: BEIS 2016, *Evidence gathering – Low Carbon Heating Technologies Domestic High Temperature Heat Pumps*.

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/565248/Heat_Pumps_Combined_Summary_report_-_FINAL.pdf [accessed 15/08/2018].

The heat pump performance standard, BS EN 14511:2013 also defines an output temperature of 55°C as ‘high temperature’. This is however subject to change in future revisions of the standard.

⁹ DECC (2014), MCS Heat Emitter Guide For Domestic Heat Pumps, Issue 2.1
https://www.microgenerationcertification.org/images/MCS_021_Issue_2.1.pdf [accessed 20/07/2018].

¹⁰ DECC (2013), Microgeneration Installation Standard: MIS 3005. Requirements for MCS Contractors Undertaking the supply, design, installation, set to work, commissioning and handover of microgeneration heat pump systems. Issue 4.3
https://www.microgenerationcertification.org/wp-content/uploads/2018/02/MIS_3005_Issue_4.3.pdf [accessed 20/07/2018].

- **Caution:** system can perform with further consideration given to heat pump design or heat pump emitters
- **Reduce:** heat pump can perform, but heat emitter sizes are likely to be excessive and therefore fabric heat loss should be considered

While in many cases installers no longer refer to the heat emitter guide directly, the heat pump system design software used by many industry professionals incorporates the heat emitter guide criteria into their calculations¹¹.

Heat pump SPF and COP

Once the heat loss of each house represented in the CHM has been calculated, the electrical requirement to meet that thermal loss for the different technologies is calculated.

For direct electric heating an efficiency of 1 is used, and therefore the electrical requirement is equal to the dwelling heat loss. For storage heaters, an efficiency of 0.95 was assumed to account for a small amount of heat loss from the heater at a time when space heating is not required. Two types of efficiency have been derived for heat pumps. The coefficient of performance (COP) is used to calculate the instantaneous electrical demand based on thermal heating demand. The COP varies with external temperature and the output flow temperature required. The seasonal performance factor (SPF), which can be thought of a weighted average of a heat pump's COPs over a heating season, is used to compare the total energy consumption of a heat pump system over a heating season with that of the incumbent system. The SPF and COP values used for ground source and air source heat pumps (both high temperature and low temperature) have been derived from literature and are detailed in Section 8.3.

Maximum household electrical limit

All homes have a maximum fuse rating for their household electricity supply. This is usually 60A, 80A or 100A depending on the age of the house and a range of other factors. Based on interviews and expert opinion, 60A is the more common household fuse rating. The maximum current draw of a heat pump was limited to 40A based on the 60A maximum household fuse rating while still allowing for background electricity use (e.g. lighting, fridge, washing machine etc.). Additionally, most domestic heat pumps tend to have a 40A fuse or less.

The same 40A maximum current limitation was used for direct electric heating. For electric storage heaters, since they charge up overnight when the rest of the household demand is minimal, they were assumed to have a maximum aggregated current draw (demand) of 55A. This assumption was also supported by industry interviews.

Heating technology merit order

In order to calculate the impact of installing the different electric heating technologies on the LV network (in the network impact model) a merit order has been applied to determine the technology installed in dwellings where more than one technology is found to be technically feasible. The merit order can be changed in the model. This will help with further investigations, when different merit orders may be investigated due to different drivers (e.g. economic drivers – not considered in this report).

The default merit order in the model is based on the technologies that have the best to the worst performance in cold conditions (in order to minimise the any LV network constraints) and are therefore in order of the heat pumps with the highest to the lowest COPs. It was further assumed that from a grid constraint perspective, storage heaters would be preferred to direct electric heating and

¹¹ Delta-ee (2018) primary research – installer interviews

thus storage heaters appear higher in the merit order than direct electric heating. The merit order is displayed in Figure 2 below.

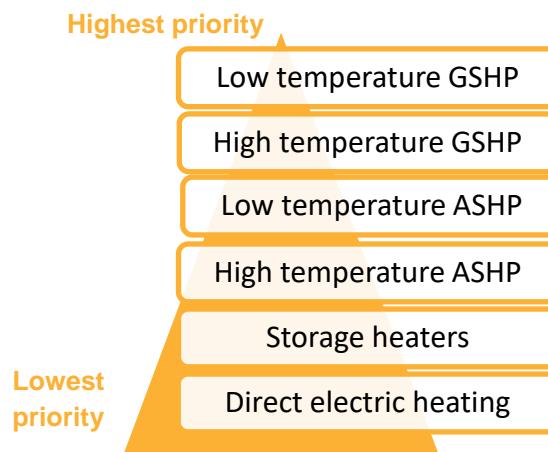


Figure 2: Default merit order of the application of different heating technologies to dwellings suited to more than one technology type – in order of the heat pumps with the best to worst COPs

To explore the impact of merit order on the uptake of electrical heating systems, and consequently the impact on the LV network, a contrasting merit order was also tested. This merit order favours ASHPs above GSHPs and is presented in Figure 3 below.

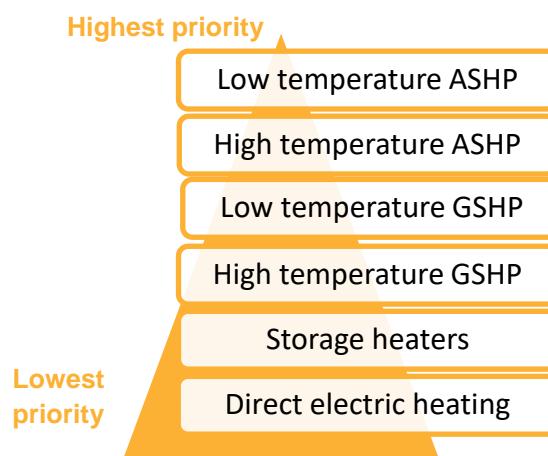


Figure 3: Alternative merit order, prioritising air source heat pumps, of the application of different heating technologies to dwellings suited to more than one technology type

Practical suitability of electric heating systems

Once the technical feasibility of the different electric heating systems was determined (based on thermal and electrical criteria), the practical feasibility of the different systems has been considered by applying a ‘practical suitability factor’ to the different electric heating systems. These practical suitability factors consider space, noise and aesthetic constraints for the different heating systems, which vary by house type. For example, we have estimated that, on average, ground source heat pumps are only suitable to 1 in 10 terraced homes due to space, noise and aesthetic constraints. This gives rise to a practical suitability factor of 10%. The proportion of terraced houses technically suitable to ground source heat pumps is then multiplied by 10% to get the number of homes both technically

and practically suited to having a ground source heat pump fitted. The factors are derived from Delta-ee expertise. Further detail regarding the practical suitability factors, as well as the factor values, can be found in Section 8.5.

Insulation levels

To model the installation of insulation, four insulation scenarios have been run in the CHM across all houses, for baseline (existing levels of insulation), and combinations of three types of insulation: loft, wall and floor.

- 1) Current state of insulation: the existing data for each house is used, representing current levels of insulation
- 2) Loft insulation: those houses which have less than 250mm of insulation have this redefined as 250mm. This is equivalent to a U-value of 0.16 W/m²K (close to a level of 0.18 W/m²K required by current building regulations). For houses with a 'room in the roof', the U-value is also improved to 0.18 W/m²K.
- 3) Wall insulation: houses which have an uninsulated cavity wall construction are recoded as having insulated cavity walls (U-value improvement from 1.60 to 0.65 W/m²K). Houses which have a solid wall construction (or defined as "other" which may be construction types such as timber frame or cob) (U-value 1.70 W/m²K) are recoded as having external wall insulation (the U-value for both internal and external solid wall insulation is the same (0.6 W/m²K) and therefore only external wall insulation was modelled, and no change in floor area from internal wall insulation was taken into account). U-values for pre and post insulation are based on best practice values from literature rather than assuming all insulation will comply with building regulations or standard U-values (e.g. those quoted in guides from the Chartered Institute of Building Services Engineers (CIBSE)). See Table 13 for references.
- 4) Floor insulation: floor construction is not a category recorded in the English Housing Survey or Living in Wales survey and therefore all houses in the CHM are assumed to have a solid floor (slab on ground, screed over insulation, U-value 0.26 W/m²K). Floor insulation is modelled to achieve U-values of 0.20 W/m²K (which is beyond those required for building regulations for a retrofit (0.25 W/m²K).

A table of U-values is given in Section 8.1, Appendix A.

3.3 Sensitivity testing

A simple one-at-a-time sensitivity analysis has been carried out to investigate the effect on the number of dwellings which could have an electrical heating system installed. The following factors have been tested:

- **Flow temperature:** ±5°C
- **Average Internal temperature:** ± 2°C
- **COP at coldest temperature:** +0.5, +1.0 (COPs are already conservative values therefore lower COPs are not tested)
- **Comfort criteria:** heat pump deemed to pass comfort criteria if guidance is "proceed" only, rather than "proceed" and "caution" (this is one of the few meaningful ways sensitivity can be tested around the heat emitter guide, a key input in the calculations)
- **Available current (Amperes/phase):** 60A (based on an 80A fuse in a house), 35A (based on a 20% increase in the existing electrical loads in the house)
- **Minimum external temperature:** -2°C (i.e. 2°C below the base temperature in each of the EHS geographic areas)
- **COP & flow temp:** -5°C flow temperature, +0.5 COP (compound sensitivity of COP and flow temperature is tested because these factors are interlinked: as flow temperature decreases, the COP of the heat pump would increase)

- **Practical feasibility of technologies:** $\pm 10\%$ of baseline practical feasibility factor

The results for the sensitivity test are reported as percentage change in number of houses suitable for electric heating systems compared to the default values used.

4 Network impacts modelling approach and assumptions

This section of the report describes the overall structure, inputs and sensitives of the low voltage network impacts model. Further justification and detail regarding the model input and assumptions can be found in Appendix B.

4.1 Model structure

The model is a Microsoft Excel based model that makes use of linear equations to derive the number of low voltage feeders¹² that would become overloaded if the homes technically suited to having an electric heating system had such a system installed. The model also calculates the number of homes that could potentially be electrified within current network limits.

There are two sets of inputs used in the network impacts model, dwelling level inputs and feeder level inputs.

Dwelling level inputs:

- Outputs from the electric heating system suitability model: technology mix and installed capacities of each heating technology in each dwelling type for each insulation scenario
- Heating technology load profiles for an average peak winter day and a 1-in-20 peak winter day
- Typical electricity load profiles of homes that do not have electric heating (baseload electricity demand)

Feeder level inputs:

- Feeder data including transformer rating, maximum recorded demand and number of customers connected
- Electric heating technology specific diversity factors

The methodology that underpins the conversion of these inputs to the desired outputs can be summarised in four steps:

Step 1: Calculation of the increase in peak load per dwelling

The percentage of each technology in each dwelling type, calculated in the electric heating system suitability model are combined with the peak winter electricity consumption profiles for the different heating technologies. This combined profile is then used to derive weighted load profiles representing the contribution each technology will make to the change in electricity demand on the feeders. The weighted load profiles and baseload dwelling electricity profile per archetype are then summed to identify an aggregate electricity load profile for a “typical” off gas grid dwelling under the new electrification scenario. By comparing this load profile to the base electricity load profile, the increase in peak load per dwelling can be calculated.

A step by step example of this process is shown for LT ASHPs in Section 9.2.

Step 2: Calculation of the current feeder utilisation and headroom

¹² ‘Feeders’ are simple radial circuits, that can be overhead or underground, that carry power to end users. A typical low voltage substation will supply 3-30 feeders.

From the feeder data provided by the DNOs, the existing headroom and utilisation factors of over 7,000 off gas grid feeders, representing over 116,000 customers, are calculated. The entire low voltage distribution network in England, Scotland and Wales has approximately 1 million LV feeders.

Step 3: Calculation of a new utilisation and headroom for each feeder for each insulation scenario

For each feeder, the increase in peak load per dwelling under each insulation scenario is multiplied by the number of customers on the feeder and a diversity factor specific to that number of customers and the technology mix in the scenario (diversity factors are covered in detail in Section 4.2). This is added to the current maximum demand on the feeder to identify the new peak demand and the resulting headroom and utilisation of the feeder for each scenario.

Step 4: Calculation of the number of feeders overloaded and the number of houses that could be identified within current network limits

Feeders with a utilisation factor of greater than 100% are deemed to be overloaded. For these feeders, the extent of overload is identified and from this the number of houses that are causing this overload. Removing these houses from the number electrified yields the number (and hence the percentage) of houses on the feeder that could be electrified within **current limits**. Therefore, the model does not consider the upgrades to the low voltage electricity network that we expect, or that need to happen, in a future scenario.

This methodology is shown graphically in Figure 4 below.

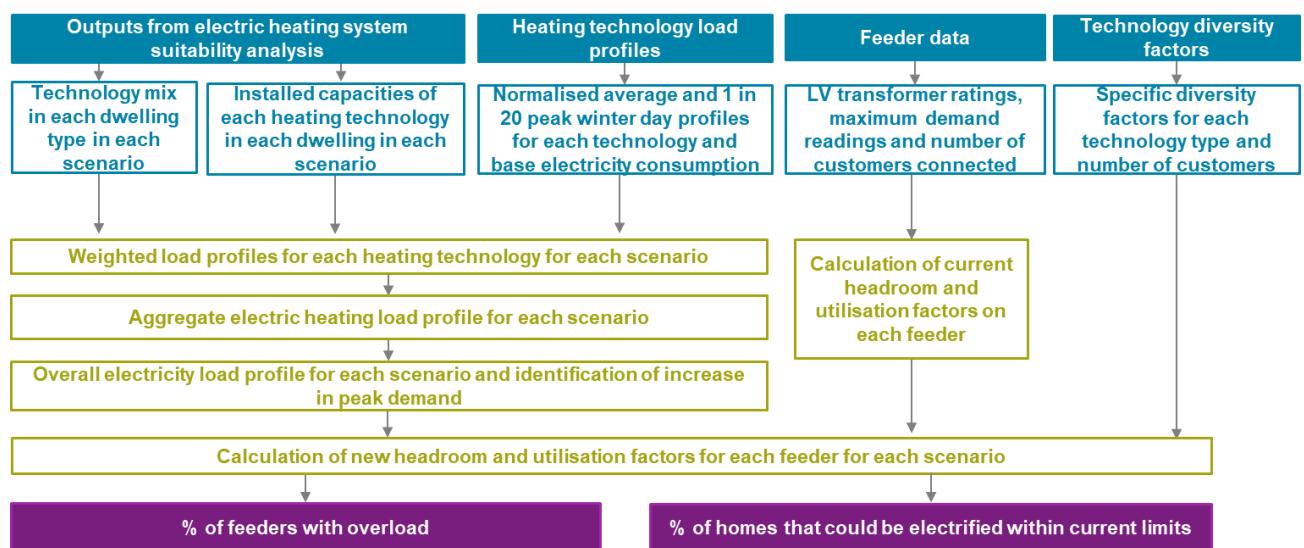


Figure 4: Methodology for network modelling

4.2 Model inputs

Distribution network operator (DNO) substation and feeder data

The DNOs active in England and Wales were contacted with a request to provide information on their low voltage networks located in rural, off-gas grid areas. The DNOs were asked to supply the following information for one or more primary substations and the associated secondary substations and feeders connected to those secondary substations:

- Substation rated capacity

- Maximum demand indicator reading for the substation¹³
- Number of customers on each feeder

More information regarding the information collected and the limitations thereof are detailed in Section 9.1 and 9.2 (Appendix B).

The model contains data for 7309 feeders, representing 116,380 off gas grid customers.

Heating technology load profiles

Measured load profiles for the different technologies for average peak winter conditions and 1-in-20 peak winter conditions are not available. Therefore, load profiles for the different technologies based on dwelling heating demand modelling have been used for this analysis, based on previous published research conducted by Delta-ee on behalf of ENWL¹⁴. The methodology used in this study is shown in Figure 5: Load profile development methodology. The profiles used are representative of typical use, and in reality, consumer behaviour could lead to alternative profiles from these simulations.

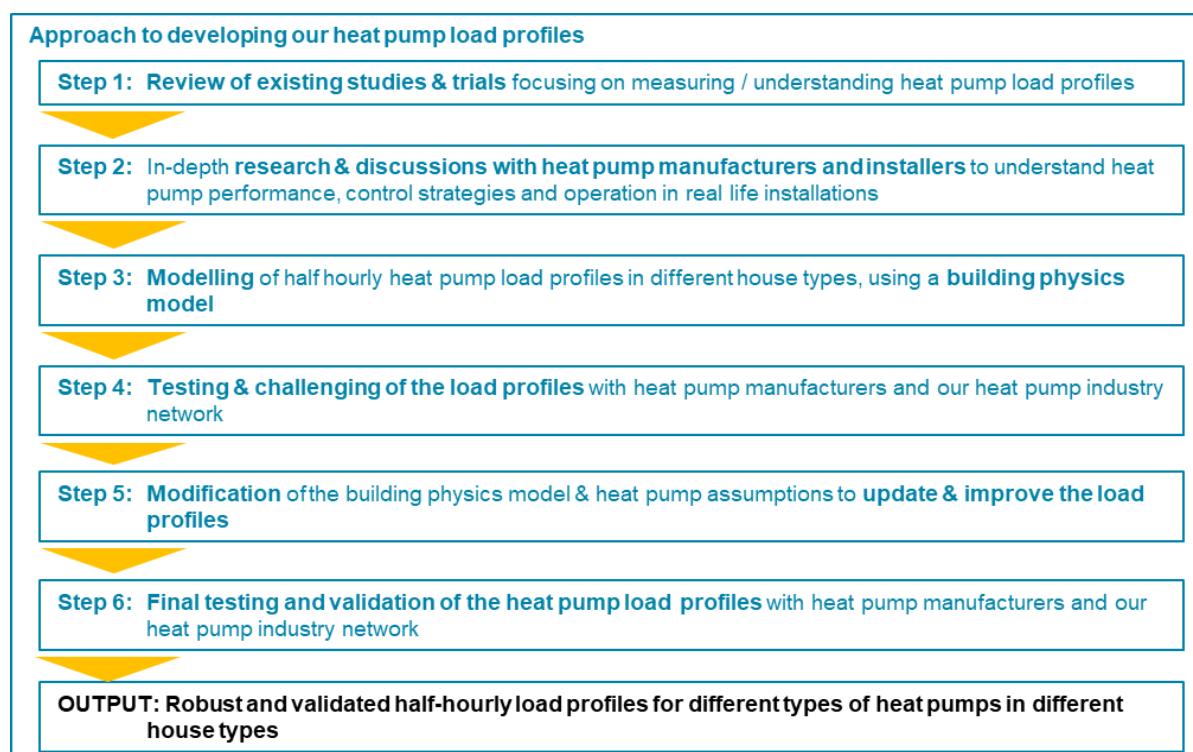


Figure 5: Load profile development methodology

The details of the different load profiles used can be found in Section 9.3 (Appendix B).

¹³ The maximum demand indicator reading is a value recorded by all substations that is the highest load the substation has supplied over a half hourly period since the maximum demand indicator reading was last reset. The value is usually recorded manually by an onsite technician during the annual substation inspection.

¹⁴ The findings in each of the five core themes presented reference the Delta-ee report presented for ENWL (2016), Managing the future network impact of electrification of heat, <https://www.enwl.co.uk/globalassets/innovation/enwl001-demand-scenarios--atlas/enwl001-closedown-report/appendix-2---delta-ee---managing-future-network-impact-of-electrification-of-heat.pdf>

Temperature scenarios

Two different temperature scenarios were used, an ‘average’ peak winter day scenario and a 1-in-20 peak winter day. The temperature data has come from the ASHRAE International Weather Files for Energy Calculations (IWEC database), with Manchester in North West of England as the reference location¹⁵.

During an ‘average’ peak winter day, temperatures are assumed to vary between -5°C and +1°C, with heating systems operating during the morning and evening heating periods to provide space heating. The designed heat pump capacity can meet the heat demand and back up heaters will typically not be required to operate.

For the 1-in-20 winter day, we have scaled down the temperatures for a number of ‘average’ peak winter days to achieve a day where the average temperature is **-5.49°C** (based on National Grid data defining -5.49°C as the daily temperature for the North West on a 1-in-20 winter day). Temperatures typically vary from -8°C to 0°C during much of this time.

During some of the heating period, the outside air temperature is lower than the ASHPs have been designed for. We’ve modelled two scenarios to investigate this:

- Back up direct electric heaters will be operating in properties with ASHP’s installed, to meet the additional heat demand
- A higher capacity ASHP has been installed. This means that the heating system comes at higher capital cost but can meet all the heat demand on the 1-in-20 peak winter day

We have assumed that GSHPs do not require back up electric heaters on either the average peak winter day or the 1-in-20 winter day, based on the ground temperatures being more stable than outside air temperatures. Therefore, the difference in performance between an average peak winter day and a peak winter day for a GSHP is assumed to be negligible.

The temperature profiles are detailed in Section 9.4 (Appendix B).

Diversity factors

Diversity factors are a measure of the probability that a particular piece of equipment will turn on coincidentally to another piece of equipment e.g. the heating systems in two different dwellings connected to the same feeder. As the number of customers increases, diversity on the network will also increase as the probability of all appliances being in use simultaneously reduces.

Diversity factors for each technology were back calculated from the After Diversity Maximum Demand (ADMD) figures, published by Northern Powergrid. ADMDs are used in the design of electricity distribution networks to identify the coincident peak load on the network for a given number of homes on an ‘average’ peak winter day, and hence the network capacity needed. The ADMD is equal to the maximum demand for one dwelling multiplied by a diversity factor. Therefore, by dividing the ADMD for a given number of dwellings by the ADMD for one dwelling we can calculate the diversity factor for that technology type and number of dwellings.

The Northern Powergrid ADMDs are based on work done as part of the Customer-led Network Revolution project. The diversity factors (for heat pumps) derived from the Northern Powergrid data range from a value of one for one property (i.e. no diversity - the maximum demand for that household is the capacity needed in the network), to 0.56 for ten properties (meaning that 56% of the households are likely to have their peak demand coincide), to 0.32 for 100 properties (meaning that only 32% of the households are likely to have their peak demand coincide).

¹⁵ Accessed February 2016.

In the modelling, we have assumed that these diversity factors apply to the ‘average’ peak winter day scenario. During 1-in-20 winter weather events, we expect heating systems will be running at full capacity to maintain the required temperature leading to negligible diversity being observed. Consequentially, we have not applied diversity factors in the 1-in-20 peak winter day scenarios.

4.3 Limitations

There are a range of simplifying assumptions and approximations in the analysis due to lack of available LV network loading data. It follows that the conclusions of the analysis should be caveated accordingly.

- All feeders are assumed to connect the same representative mix of dwelling types. This is unlikely to reflect reality, where some feeders have a higher percentage of detached houses than average whereas others may connect only to terraces. Further sensitivity testing is required.
- Transformer utilisation (based on maximum demand indicator values) has been used as a proxy for overall LV network utilisation, due to the lack of availability of more granular feeder data. Other factors that affect the capacity headroom of individual feeders have not been considered. This includes voltage drop, phase load balance, and how demand is distributed between sections and branches of cables and we recommend further analysis is done on these variables.
- Maximum demand readings are half-hour averages, so short duration spikes will not have been captured in these results. However, this should not significantly impact the results as transformers and cables typically have a degree of thermal inertia which means they can handle loads more than their rating for brief periods without excessive temperature rise. The maximum demand values could have also been unduly affected by large short-term current surges unlikely to occur again and transformers being back-fed.
- Pole-mounted transformers, common in off-gas grid areas, may be under-represented in the data set due to maximum demand reading not always being recorded for these transformers as they are difficult for technicians to access.
- The mix of heating technologies has been determined based on the technical feasibility of each technology in the housing segments, combined with a merit order for each technology based on energy savings delivered. In reality, uptake of each technology will not follow this order. Instead, it will be driven by a combination of factors, including upfront capital cost, energy cost savings, consumer perception, installer attitudes and government support mechanisms. These factors are out of scope for this project but should be considered in future analysis.
- Average installed capacities have been assumed for all dwellings. There is a risk that there might be a higher proportion of higher capacity heat pumps installed on specific feeders than average.

Further assumptions can be found in Section 9.2, Appendix B.

4.4 Options available to accommodate additional electric heating load on the low voltage network

There are a number of different measures that could be implemented to reduce the electric heating load on the LV feeders during peak times. These include:

1. More efficient electric heating through increasing system efficiency
2. Increase heat pump capacity to allow 1-in-20 peak load to be met through heat pump operation alone, reducing use of direct electric back up
3. Shift the demand for peak heat using smart controls.
4. Shift the demand for peak heat using thermal energy storage

5. Shift the demand for peak heat using electrical battery storage.

These measures are discussed in more detail in Section 6.3 of the results.

Theoretically, the above measures could reduce the additional peak load to zero by moving all additional heating loads from peak demand periods. However, this would come at significant capital cost for customers and is unlikely to occur without financial or regulatory intervention. Since these are outside of scope of this project, a high-level approach has instead been taken to identifying the impact that implementing these solutions has on the network. We've tested the impact a 20%, 50% and 70% reduction in peak load has on the percentage of low voltage feeders overloaded, which could be achieved through a combination of the measures described above.

5 Electric heating system suitability results

The full detailed results and calculations can be found in the accompanying Electric Heating System Suitability Excel model. The results below are extracts from the model outputs.

5.1 Technical feasibility of electric heating systems

This section addresses the proportion of off-gas grid houses that can technically have an electric heating system installed in their current state. Table 1 gives the results from the model for the existing level of insulation in each house – baseline modelling where no additional insulation has been added.

Table 1: Number of off-gas grid homes that would be suitable for different electric heating technologies with existing levels of insulation, based on technical suitability. Analysis based on 1,309,187 off gas grid dwellings in England and Wales in total.

	At least one type of electric heating	Low temp. ASHP	High temp. ASHP	Low temp. GSHP	High temp. GSHP	Direct electric heating	Storage heaters
Proportion of homes	91%	70%	73%	80%	82%	52%	66%
Numbers of homes	1,190,000	923,000	953,000	1,040,000	1,070,000	679,000	868,000

Overall, 91% of houses are found to be suitable¹⁶ for at least one type of electrical heating system in their current state. More houses are suitable for a high temperature than low temperature heat pump technology. The greater suitability of high temperature systems indicates that meeting the comfort criteria (specified by the MCS heat emitter guide) is more of a barrier than the available current (Amps per phase) of dwellings. GSHPs are found to be more widely suitable than ASHPs, due to their higher COPs that can be achieved with this technology, requiring a smaller connection capacity. Storage heaters and direct electric heating are less suitable to a greater proportion of homes than the heat pumps due to their electricity demand exceeding the maximum available current of dwellings in more instances than the heat pumps. Storage heaters are suitable for more homes as the model allows storage heaters to draw more current (55A compared to 40A for direct electric heating) since they charge up over night when all other household electric loads are at a minimum.

5.2 Technical feasibility of electric heating systems following energy efficiency improvements

This section gives the proportion of off-gas grid areas that can technically have an electric heating system installed following the installation of insulation. Three insulation scenarios have been considered: loft insulation (virgin and top-up), loft & wall insulation (cavity, or solid wall), and loft & floor insulation. Figure 6 gives the results from the model for the proportion of off-gas grid homes that would be suitable for different electric heating technologies with improved levels of insulation compared to the existing levels of insulation.

¹⁶ Note the results of Sections 5.1 to 5.4 do not consider practical feasibility factors such as space availability

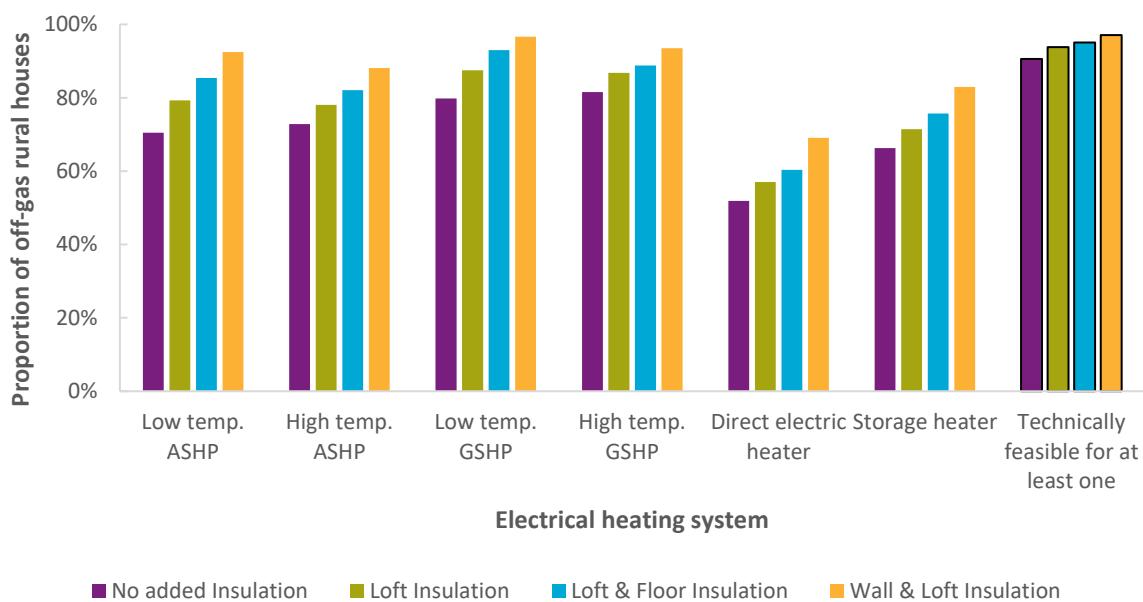


Figure 6: Proportion of off-gas grid homes that would be suitable for different electric heating technologies with improved levels of insulation, based on technical suitability

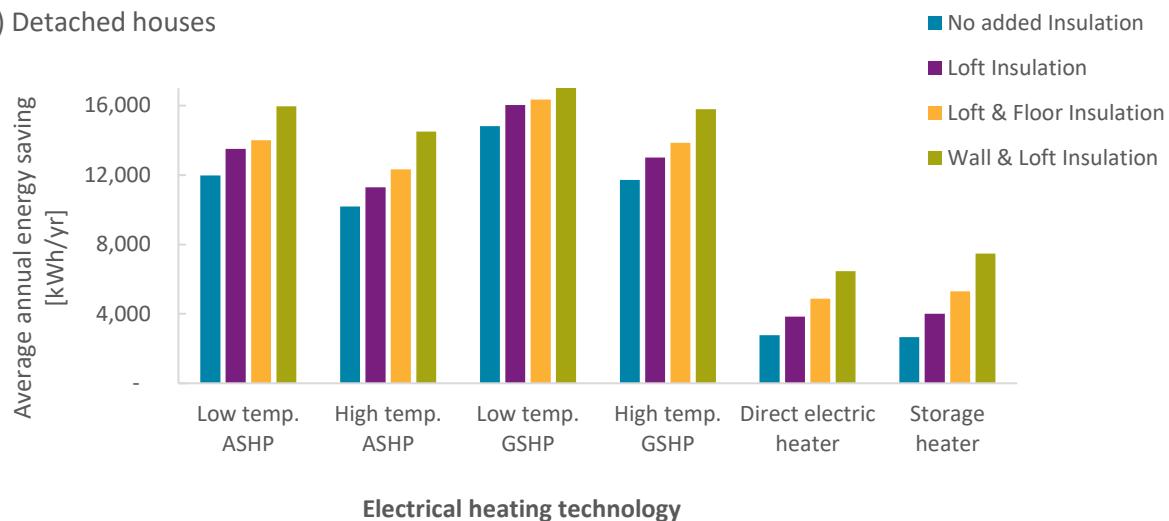
Figure 6 shows that in all cases the addition of insulation measures improves the proportion of homes suitable to electric heating. Across the different insulation scenarios, improvements in wall & loft insulation result in the largest proportion of homes being suitable for electric heating systems. Wall & loft insulation reduces the dwelling heat losses more than the other insulation measures. This lower heat loss allows for a heat pump with a smaller capacity to be installed, which in turn has a lower electricity requirement. Furthermore, according to the heat emitter guide, lower specific heat losses make the thermal comfort criteria easier to meet and therefore achievable for a greater proportion of homes.

5.3 Level of energy savings that can be achieved by electric heating systems

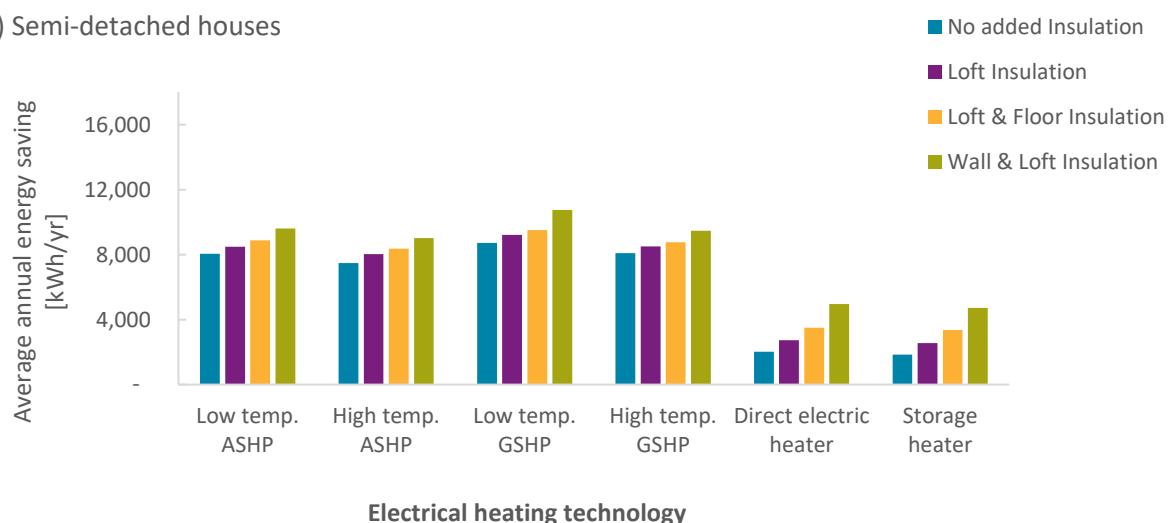
This section shows the level of energy saving that can be expected for different technologies and levels of insulation compared to the incumbent heating system. Energy savings will lead to cost savings and a reduction in CO₂ emissions associated with a dwelling's space heating, both of which will depend on the incumbent heating system of the dwelling.

Figure 7 shows these average annual energy savings across three types of houses. The highest energy savings are found for detached houses, reflecting a higher energy consumption for the incumbent heating system. Across the technologies, GSHPs enable the highest energy savings, and low temperature heat pumps offer higher savings than high temperature systems; this pattern reflects the seasonal performance factor (SPF) for each technology. Energy savings are lowest for the direct electric and storage heaters, and in fact for some houses the energy demand calculated by the model was found to increase.

a) Detached houses



b) Semi-detached houses



c) Terraced houses

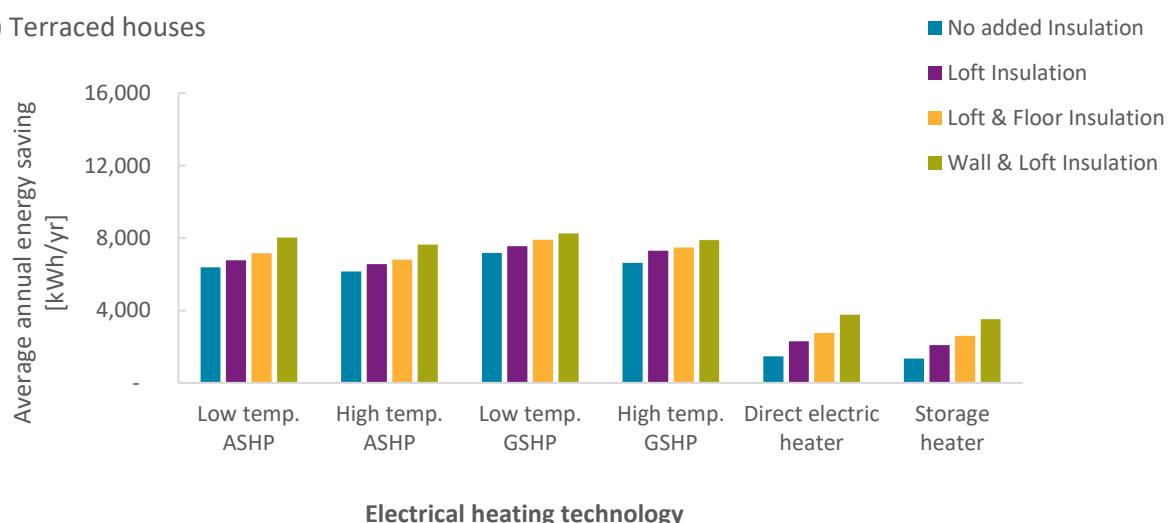


Figure 7: Average annual energy savings from electrical heating systems and additional insulation for a) detached houses, b) semi-detached houses, and c) terraced houses

5.4 Sensitivity testing

Key factors that affect the number of houses which are suitable for electric heating systems are shown in the sensitivity results in Table 2 and Figure 8.

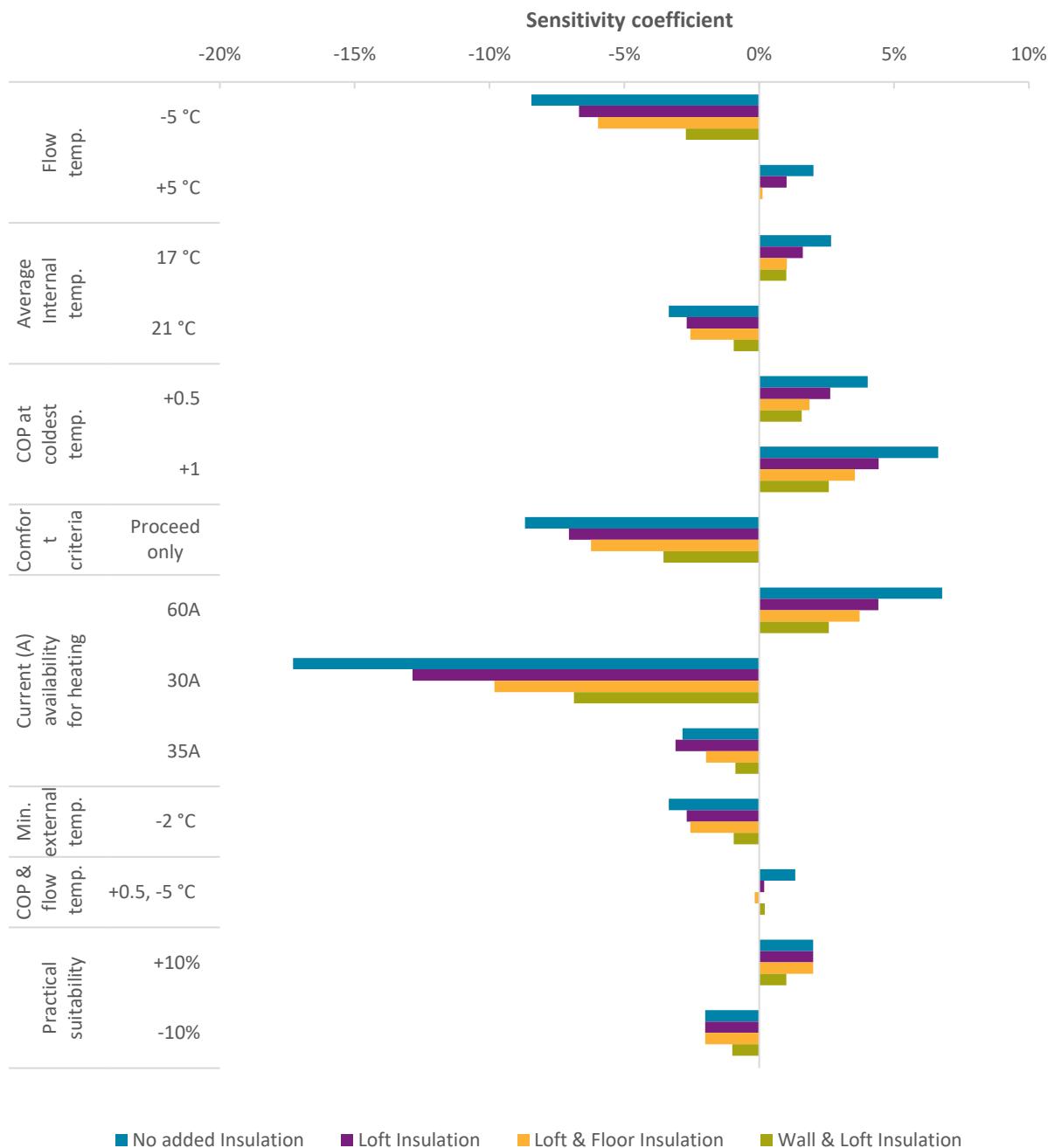


Figure 8: Sensitivity analysis for number of dwellings that are suitable for at least one type of electric heating system. The sensitivity coefficient (x-axis) indicates the change in overall suitability from the central assumption, in the proportion of homes suitable for at least one technology.

Table 2: Sensitivity analysis for electric heating system suitability. Percentages show the variation in numbers of homes suitable from the central assumptions.

		Flow temp.		Average internal temp.		COP at coldest temp.		Comfort criteria Proceed only	Available current (per phase)		Minimum external temp. -2°C	COP & flow temp.* COP: +0.5 Flow: -5°C
	Change in model input →	-5°C	+5°C	17°C	21°C	+0.5	+1		60A	35A		
Low temp. ASHP	Existing insulation	-65%	8%	9%	-9%	8%	11%	-70%	10%	-6%	-9%	-64%
	Loft Insulation	-70%	6%	8%	-10%	6%	10%	-79%	8%	-6%	-10%	-70%
	Loft & Floor Insulation	-68%	2%	4%	-8%	7%	9%	-85%	8%	-4%	-8%	-68%
	Wall & Loft Insulation	-67%	0%	2%	-5%	3%	6%	-92%	4%	-5%	-5%	-66%
High temp. ASHP	Existing insulation	0%	0%	7%	-4%	14%	21%	0%	17%	-6%	-6%	14%
	Loft Insulation	0%	0%	6%	-4%	13%	17%	0%	14%	-6%	-6%	13%
	Loft & Floor Insulation	0%	0%	4%	-5%	10%	14%	0%	11%	-6%	-6%	10%
	Wall & Loft Insulation	0%	0%	3%	-2%	7%	9%	0%	8%	-4%	-4%	7%
Low temp. GSHP	Existing insulation I	-74%	10%	8%	-7%	2%	4%	-80%	4%	-2%	-2%	-73%
	Loft Insulation	-78%	7%	7%	-8%	2%	3%	-88%	3%	-2%	-2%	-78%
	Loft & Floor Insulation	-76%	2%	2%	-8%	2%	3%	-93%	4%	-2%	-2%	-75%
	Wall & Loft Insulation	-70%	0%	1%	-2%	2%	3%	-97%	3%	-1%	-1%	-70%
High temp. GSHP	Existing insulation	0%	0%	4%	-4%	10%	13%	0%	12%	-5%	-5%	10%
	Loft Insulation	0%	0%	2%	-4%	7%	9%	0%	8%	-7%	-7%	7%
	Loft & Floor Insulation	0%	0%	2%	-3%	6%	8%	0%	7%	-4%	-4%	6%
	Wall & Loft Insulation	0%	0%	1%	-3%	3%	5%	0%	4%	-5%	-5%	3%
Direct electric	Existing insulation			6%	-8%				21%	-10%	-10%	
	Loft Insulation			4%	-6%				21%	-10%	-10%	
	Loft & Floor Insulation			5%	-5%				21%	-5%	-5%	
	Wall & Loft Insulation			5%	-5%				19%	-7%	-7%	
Storage heaters	Existing insulation			5%	-6%				18%	-6%	-6%	
	Loft Insulation			5%	-7%				17%	-7%	-7%	
	Loft & Floor Insulation			4%	-6%				14%	-6%	-6%	
	Wall & Loft Insulation			4%	-4%				11%	-5%	-5%	
At least one technology	Existing insulation	-8%	2%	3%	-3%	4%	7%	-9%	7%	-3%	0%	1.30%
	Loft Insulation	-7%	1%	2%	-3%	3%	4%	-7%	4%	-3%	0%	0.20%
	Loft & Floor Insulation	-6%	0%	1%	-3%	2%	4%	-6%	4%	-2%	0%	-0.20%
	Wall & Loft Insulation	-3%	0%	1%	-1%	2%	3%	-4%	3%	-1%	0%	0.20%

* compound sensitivity of COP and flow temperature is tested because these factors are interlinked: as flow temperature decreases, the COP of the heat pump would increase.

These results show that the greatest sensitivity is related to the heat emitter guide comfort criteria indicators; both changing the criteria to 'proceed' only and reducing the flow temperature would greatly reduce the number of houses suitable for low temperature heat pumps. The sensitivities of these criteria are much lower when looking at the numbers of dwellings that could be suitable at least one type of electrical heating system. Many dwellings would therefore still be suitable for a different electric heating system type (high temperature heat pump, direct electric heating or storage heaters) if these criteria were changed.

In addition to considering each sensitivity criteria separately, we have shown the compound effect of COP and flow temperature as these are not independent (a reduction in flow temperature would lead to a higher COP and vice versa). For low temperature heat pumps, there is minimal change in the sensitivity compared to the flow temperature factor alone. This shows that even if the COP is improved at lower flow temperatures, the flow temperature is an important limiting factor for the suitability of a heat pump for a house (and in many houses in this analysis, the limit lies between 35 and 40 °C). For high temperature heat pumps, flow temperature is not a technical barrier and therefore there is no difference in the sensitivity compared to the COP factor alone. Overall, however the number of houses that could adopt at least one type of electric heating system has very low sensitivity to this compound effect, suggesting that any houses which are prevented from adopting a low temperature heat pump are able to adopt a high temperature heat pump.

The available current (Amperes per phase) of each house is a factor which is sensitive for the direct electric heaters, storage heaters and high temperature heat pumps. For houses which have a larger fuse rating (80A or 100A), these technologies are more frequently suitable. Conversely, they are the most sensitive to a house having a high electrical power draw for other appliances within the house.

Table 3 gives the sensitivity of the number of houses suitable for at least one type of electrical heating system to changes to the practical feasibility factors. The practical feasibility factors are discussed in further detail in Section 5.5.

Table 3: Sensitivity of number of houses suitable for at least one type of electrical heating system to practical feasibility factors. Practical suitability has a direct relationship to the proportion of feasible houses for individual electrical heating systems (i.e. a 10% increase in practical suitability increases the number of suitable houses by 10%) therefore these have not been included in the table.

	Practical suitability	
	+10%	-10%
Existing insulation	2%	-2%
Loft Insulation	2%	-2%
Loft & Floor Insulation	2%	-2%
Wall & Loft Insulation	1%	-1%

Practical suitability has a linear relationship with the number of suitable houses for each **individual** electrical heating system, showing that the results are very sensitive to this practical suitability factors assigned. However, the total number of houses which are suitable for at least one type of electrical heating system is not strongly affected by the practical suitability of each heating system, showing that most houses have a choice of heating system that can be installed.

5.5 Major barriers to the technical and practical feasibility of electric heating

This section addresses the major barriers to technical feasibility of electric heating. These major barriers are identified from the sensitivity analysis and from consideration of the practical feasibility of electric heating systems.

Learnings from sensitivity analysis

The sensitivity analysis has enabled us to identify the following barriers:

- **Internal temperature:** higher expectations or requirements of internal temperatures will compromise the ability of a heat pump to deliver a sufficient level of thermal comfort at coldest winter times. The effect is mainly for low temperature heat pumps, and the barrier reduces for any house as it is better insulated.
- **Colder winter temperatures:** If heating systems are designed based on colder minimum winter temperatures, the electrical requirements of the heating systems are likely to be greater and fewer houses may be suitable. However, if the design minimum temperature remains the same but winter temperatures regularly fall below this minimum, it is likely that they will fail to deliver sufficient thermal comfort during peak winter times and may develop an unsatisfactory reputation which would pose a barrier to uptake. The results of the sensitivity analysis show that a 2°C colder design winter temperature would not affect the number of homes suitable for an electrical heating system, but the most suitable type of system may change.
- **Heat emitter size:** if it is not practical to replace existing heat emitters within a house, low temperature heat pumps are likely to be unsuitable in many homes (this point is addressed in greater detail in Section 5.7)
- **Available current (Amperes per phase) for electrical heating system:** this barrier depends on the house's fuse rating and existing wiring. The sensitivity analysis shows that a lower available current has the greatest effect on direct electric heating, but also has a significant reduction (around 5%) on the number of houses which can adopt electrical heating systems across all heating systems.

Practical feasibility

The practical factors affecting the adoption of electric heating systems are mainly focussed on the space constraints of a dwelling for fitting in the heat pump units. Internally these are the expander/compressor units, buffer tank and hot water tanks for delivering domestic hot water. Externally, these are the fan units or ground coils/boreholes (which would require a garden). For direct electric heating and storage heaters, the main consideration is the available internal wall surface area. In addition to space constraints, aesthetic and noise considerations are considered. Heat pump units are considered by some to be unattractive, especially if they take up a larger space than the heating system they are replacing, and large storage heater units in a living space may be rejected on aesthetic grounds. Finally, practically feasibility also includes a 'hassle factor' which can put off many households from making changes to their home heating system. For example, some households may choose not to adopt direct electric heating or storage heater units if it would require them to rewire a house's internal electricity circuit. Further detail regarding the practical suitability factors, as well as the factor values, can be found in Section 8.5, Table 14.

Figure 9 shows the proportion of off-gas grid dwellings that are found to be suitable for electric heating systems when both technical and practical factors are considered.

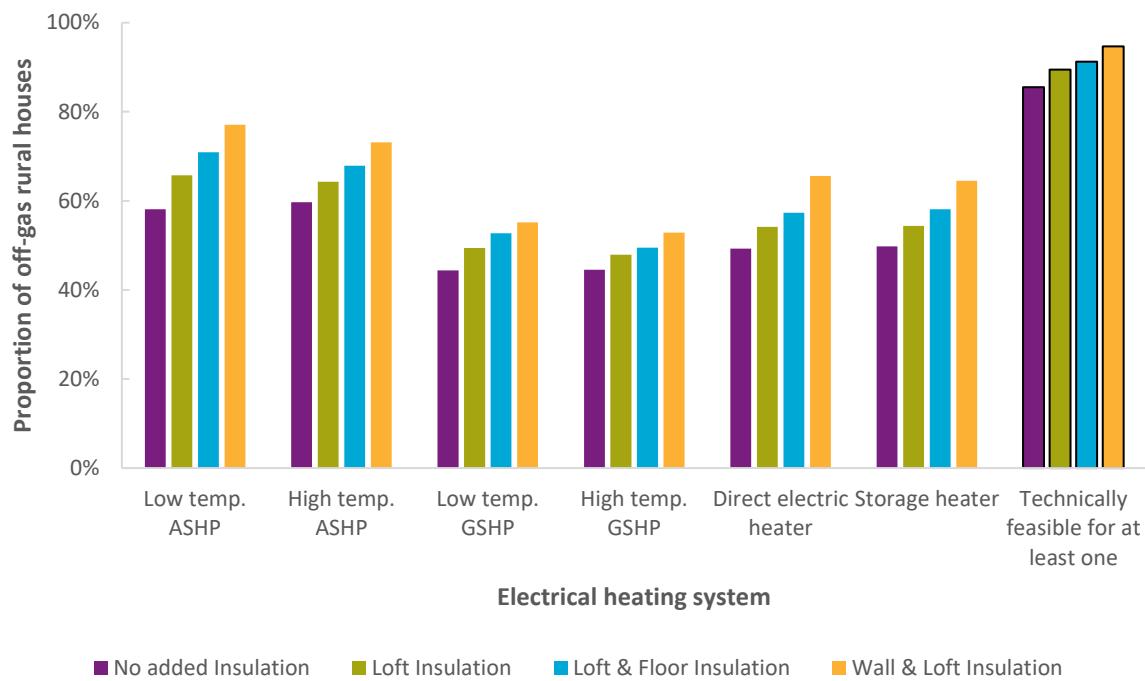


Figure 9: Suitability of houses for electric heating considering both technical and practical factors

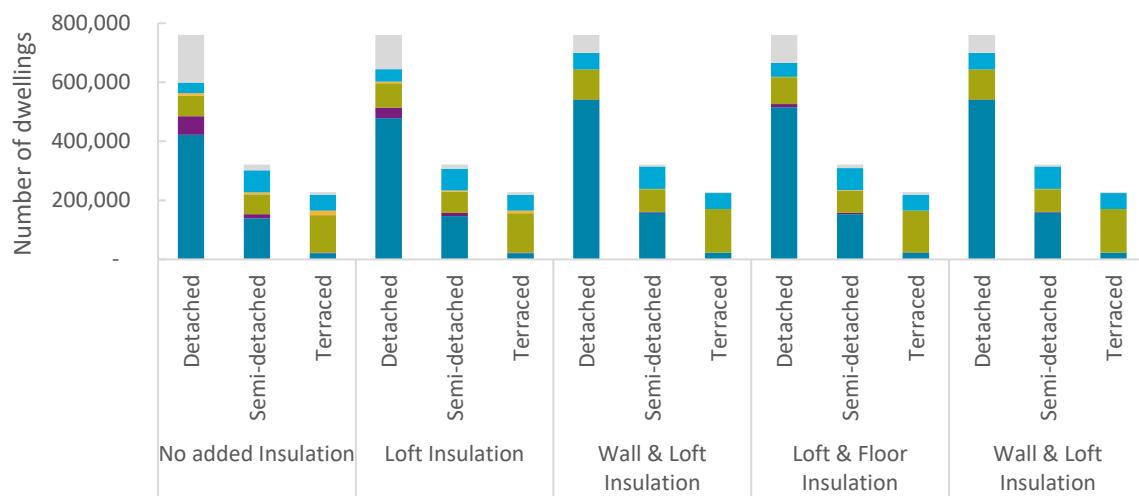
The reduction in number of suitable houses is around 14% for ASHPs and around 40% for GSHPs. However, overall there is a 5% reduction in the number of houses which could have any electrical heating system in their current state, reducing to 2% if houses have wall & floor or loft insulation installed to improve efficiency.

5.6 Application of the merit order to determine installed technology base

In order to model the impact that large scale electric heating would have on local low voltage networks in rural areas, an order of preference for electric heating systems has been applied to choose the technology deemed to be installed in houses that are suitable for multiple options. Figure 10 shows the theoretical breakdown of the installed base of electric heating systems in off-gas grid homes if all homes suited to electric heating have it installed. The results are shown for two alternate merit orders. Figure 10 a) shows the uptake of electric heating systems for the merit order where the system with the best possible COP, as in accordance with the merit order given in Figure 2 (Section 3.2), is used. Figure 10 b) shows an alternate merit order where ASHPs are the preferred technology, in accordance with Figure 3 (Section 3.2).

Figure 10 a) shows how even by considering both technical and practical feasibility, LT-GSHPs make up the majority (56%) of installations in detached homes, where they are most practically suited to being installed. Across the dwelling types this leads to over 500,000 homes being theoretically suitable to GSHPs. The reason this number is so large is that GSHPs appear first on the merit order used (which is based on best to worst case COPs). There is still a large proportion of detached homes (21%) that are not suitable to any form of electric heating due to their high heat losses. Electric heating systems are suitable in a greater proportion of semi-detached and terraced houses.

a) Merit order based on best to worst COP



b) Merit order based on ASHP priority

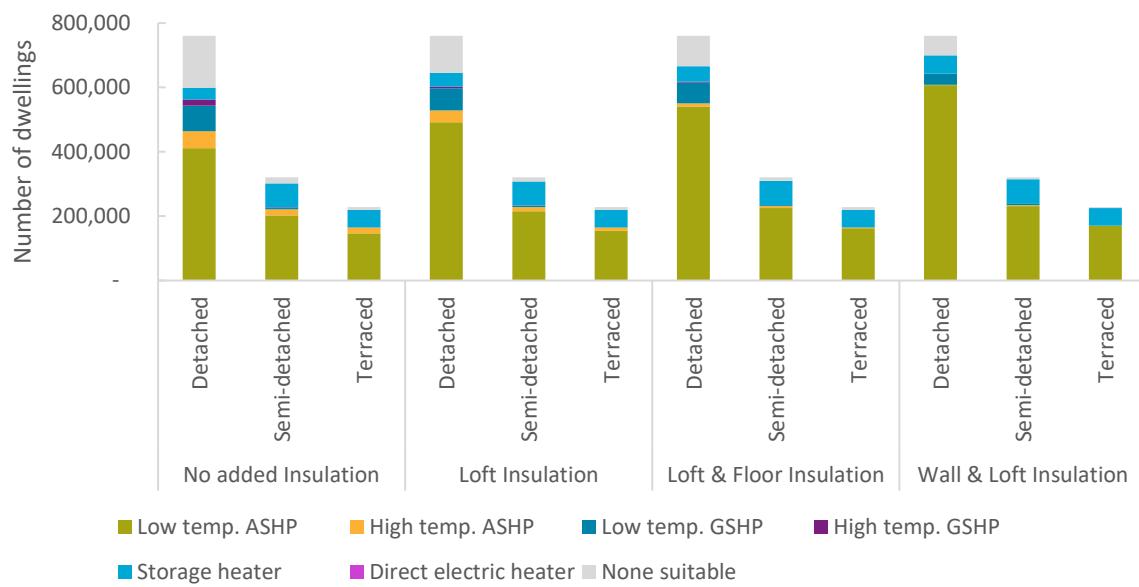


Figure 10: Uptake of each electrical heating system for each house type and insulation improvement level based on a) best to worst COP merit order and b) ASHP priority, considering both technical and practical suitability. There are 1,309,187 off gas grid dwellings in total within the modelling.

Figure 10 b) shows that in detached and semi-detached houses, the technology given highest priority in the merit orders is the dominant technology. For terraced houses, low temperature ASHP are more prevalent compared to GSHPs in Figure 10 a) due to practical issues making the installation of GSHPs more difficult. When ASHPs appear highest on the merit order, across the dwelling types, this leads to over 700,000 homes being theoretically suitable to ASHPs.

5.7 Homes requiring an upgrade to their heating distribution system

This section addresses the proportion of the off-gas grid housing stock that are likely to require an upgrade to their heating distribution system if electrical heating systems are installed. This has been considered using criteria from the heat emitter guide, and also based on dialogue with heat pump installers.

Our first approach to estimating the proportion of houses that would require an upgrade to their heating distribution system is to consider the guidance given in the MCS heat emitter guide. The guidance table recommends whether changes to the house are required for the heat pump to deliver a satisfactory level of comfort to the household. Thus far, a house has been considered suitable for a heat pump if the heat emitter guidance was categorised as "proceed" or "caution". As described in Section 3.2, the category of "caution" suggests that the heat emitters may need further consideration, and therefore, assuming these dwellings all need an upgrade to their heating distribution system, the proportion of dwellings this applies to can be calculated from the model. These results are shown in Figure 11. Based on this assumption, all installations of low temperature heat pumps require an upgrade to the heating distribution system, and high temperature heat pumps do not require this upgrade. Overall, 9% of houses are estimated to require a heating distribution system upgrade to allow for any type of heat pump to be installed.

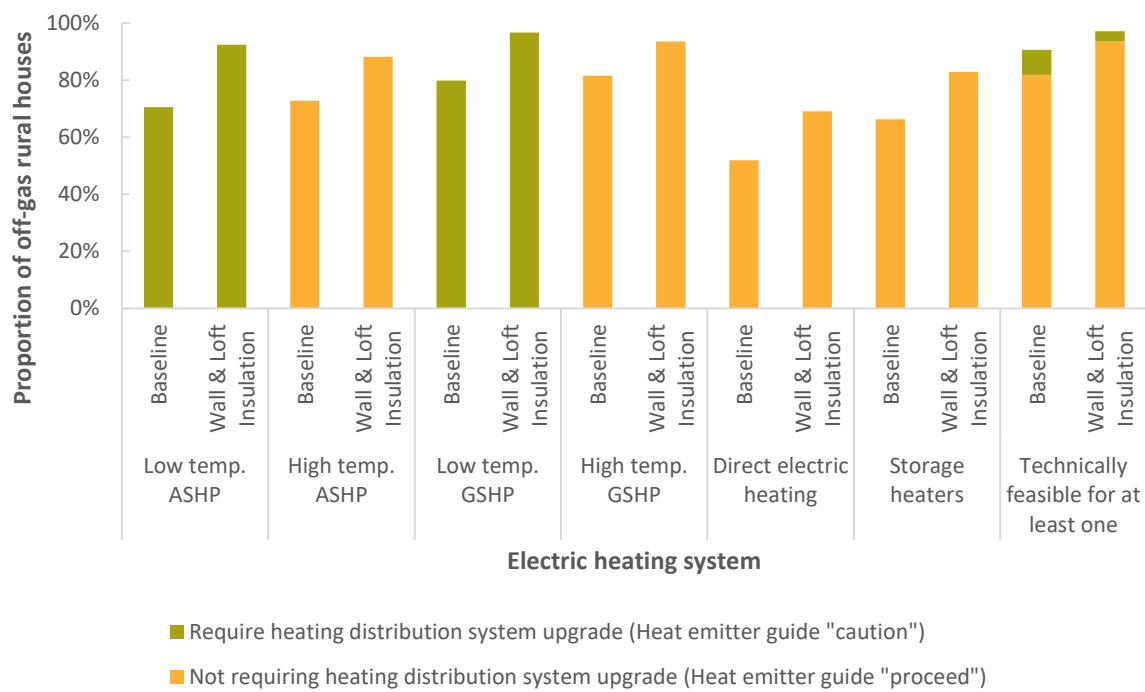


Figure 11: Split of houses that would or would not likely require an upgrade to their heat distribution system based on the assumption that the heat emitter guide categories of "proceed" would not require an upgrade and "caution" would require an upgrade.

Based on interviews with heat pump manufacturers, installers, utilities and existing Delta-ee insight, the existing heat emitters need to be replaced (or additional emitters added) more than 80% of the time when installing a low temperature heat pump. Some sources claim that in all cases they need to replace the existing radiators when installing a low temperature system.

In the case of high temperature systems, our research indicates that they will need replacing in roughly 25% of retrofits. In cases where they do need replacing, this is usually because the system has been designed to use >80°C flow temperatures prior to the introduction of condensing boilers resulting in smaller radiators.

Where the existing radiators are relatively recent, and / or the homeowner wants to minimise costs, the existing radiators may be used and (space permitting) an additional radiator will be added to the same room to increase output. In both the case of high temperature and low temperature systems where the existing radiators are nearing the end of life, they would require replacing even if the

incumbent system were being replaced like-for-like. Radiators have a lifespan of approximately 20 years and as they become older they become rusted (internally and externally), filled with sludge and start to leak (due to worn out seals). As they age their efficiency is reduced and the radiators can start to introduce contaminants (such as rust, oil and air) into the hydronic system causing issues for other newer radiators of the heating system and heat exchangers in heat supply plant.

Underfloor heating is much less common than radiators in homes using oil boilers. One installer indicated that 60% of existing underfloor systems, if designed to be used with an oil boiler, required replacement when fitting a low temperature heat pump system. Due to the disruption associated with installing underfloor heating, it is more commonly present in higher end new builds and when an extension is added, or a significant refurbishment is being undertaken.

6 Network impact of electrification of off gas grid heating

6.1 Limitation of the low voltage electricity network to the adoption of electric heating

This section addresses limitations from the low voltage electricity distribution network, by estimating the proportion of off gas grid homes that can have electric heating fitted without feeders exceeding their current capacity. We have tested all four of the insulation scenarios below and compared them to a base case of the current network utilisation:

- Existing levels of insulation (baseline scenario in the electric heating system suitability model)
- Loft insulation
- Wall & loft insulation
- Floor & loft insulation.

The distribution of electric heating technologies has a significant impact on the percentage of low voltage feeders that could overload. Uptake of these technologies is unlikely to be driven by energy savings alone, as assumed above. Therefore, we have tested the network impact under two different technology merit order scenarios:

- Energy saving merit order – where the heat pumps with the highest COP are installed in homes as a matter of preference¹⁷. This is the same merit order displayed in Figure 2 (Section 3.2).
- Air source heat pumps preferred due to practical considerations installation preference merit order¹⁸. This is the same merit order displayed in Figure 3 (Section 3.2).

Energy Savings Merit Order

In the energy saving merit order scenario, the deployment of LT-GSHPs dominates the technology mix, as shown in Table 4.

Table 4: Technology mix deployed in the Energy Savings merit order scenario

% Of dwellings	Existing levels of insulation	Loft insulation	Wall & loft insulation	Floor & loft insulation
HT-ASHP	2%	1%	0%	0%
LT-ASHP	20%	22%	25%	23%
HT-GSHP	6%	4%	0%	1%
LT-GSHP	44%	49%	55%	53%
Direct Electric	0%	0%	0%	0%
New Storage Heaters	13%	13%	14%	13%
Existing Storage Heaters	1%	1%	0%	0%
Non-Electric	14%	10%	5%	8%

Table 5 shows the percentage of feeders overloaded in each of the four insulation scenarios if every dwelling identified as being suitable was electrified. The proportion of homes that could be electrified

¹⁷ In accordance with the heating technologies' efficiencies (COP in the case of the heat pumps) this leads to the merit order, from most to least preferable: LT-GSHPs, HT-GSHPs, LT-ASHPs, HT-ASHPs, storage heaters, direct electric heating.

¹⁸ Merit order, from most to least preferable: LT-ASHPs, HT-ASHPs, LT-GSHPs, HT-GSHPs, storage heaters, direct electric heating.

within the current feeder capacity is also shown. Overloaded feeders have been defined as feeders with a utilisation factor above 100%.

Table 5: Proportion of households that can have electric heating fitted considering low voltage network constraints (Energy Savings merit order scenario – GSHPs are prioritised over ASHPs)

Scenario	% of dwellings with electric heating	Increase in peak load (kW/dwelling)	% of feeders overloaded	% of dwellings that could be electrified within feeder limits
Base case				
Average peak winter day	24%	0	1%	N/A
Existing levels of insulation				
Average peak winter day	86%	2.45	13%	84%
1-in-20 peak winter day - larger ASHP with no back up electric	86%	2.60	28%	67%
1-in-20 peak winter day - ASHP with back up electric	86%	4.03	33%	64%
Loft insulation				
Average peak winter day	90%	2.46	12%	88%
1-in-20 peak winter day - larger ASHP with no back up electric	90%	2.63	28%	70%
1-in-20 peak winter day - ASHP with back up electric	90%	4.06	33%	66%
Wall & loft insulation				
Average peak winter day	95%	2.24	10%	93%
1-in-20 peak winter day - larger ASHP with no back up electric	95%	2.47	27%	75%
1-in-20 peak winter day - ASHP with back up electric	95%	3.90	32%	71%
Floor & loft insulation				
Average peak winter day	92%	2.33	12%	89%
1-in-20 peak winter day - larger ASHP with no back up electric	92%	2.50	27%	72%
1-in-20 peak winter day - ASHP with back up electric	92%	3.93	33%	68%

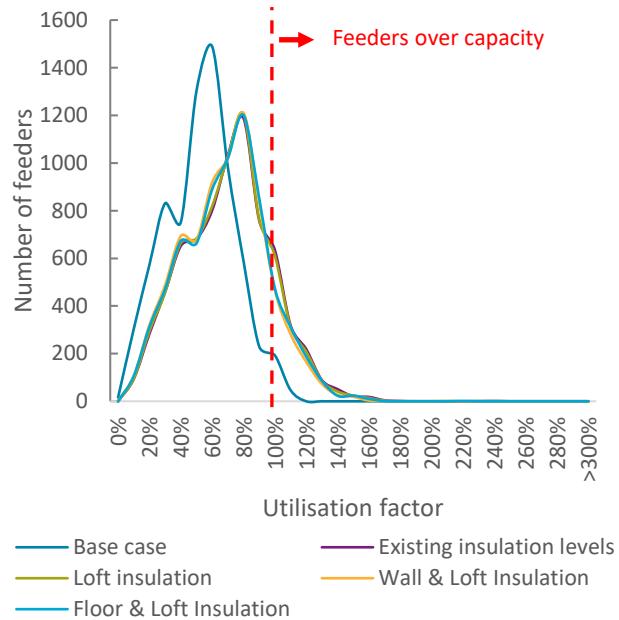
The extent of network overload is similar in all four insulation scenarios due to the reduction in heating load per dwelling being counteracted by an increased percentage of houses where electrification is technically possible. For example, in both the existing insulation levels scenario and the wall & loft insulation scenario 10-13% of feeders are overloaded. However, the percentage of dwellings electrified has increased from 86% to 95%.

The percentage of feeders overloaded is lowest in the average peak winter day scenario, with only 10-13% of feeders being overloaded across the different insulation scenarios. This is as expected, as thermal demand is lowest in this scenario and efficiency of heat pump operation is highest. The percentage of feeders overloaded is highest in the 1-in-20 peak winter day scenario where ASHPs are augmented with direct electric heaters to meet the additional heat load. In this case, feeder

overload more than doubles, to 33%. This is demonstrated by the move to the right in the feeder distributions shown in

Figure 12.

a) Average peak winter day



b) 1 in 20 peak winter day (back up electric heaters)

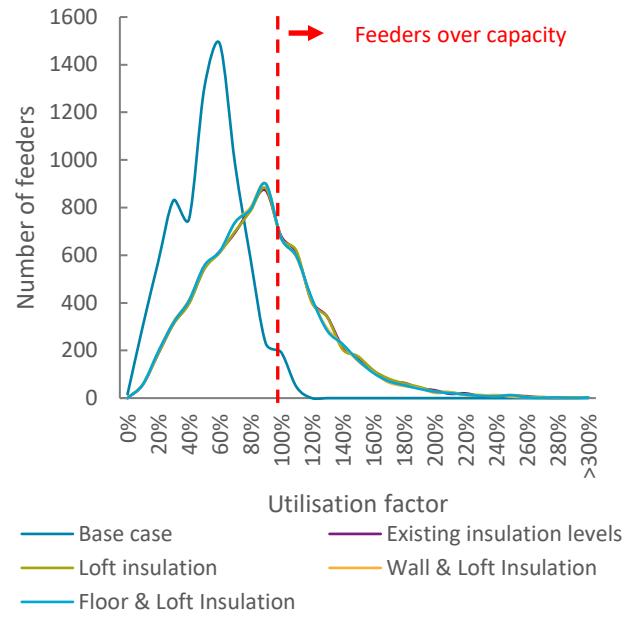


Figure 12: Distribution of feeder utilisation factors for a) average peak winter day and b) 1-in-20 peak winter day (back up electric heaters) scenarios. The area under curves exceeding 100% utilisation factor is proportional to the percentage of feeders overloaded.

There is a large amount of variation in feeder characteristics, allowing some feeders to have high levels of electrification without overloading the network, whereas others would require significant reinforcement.

Figure 13 shows the impact that electrifying each off-gas grid low voltage feeder in turn has on the total percentage of off gas grid homes electrified, starting with the feeders which have a greatest impact i.e. a large number of houses that can be electrified within current network limits. The dotted line shows the impact from electrifying all dwellings where it is technically possible to do so at the dwelling level based on the outputs of the heating system suitability model, whereas the solid line includes only the homes which can be electrified without overloading the feeder. For both insulation scenarios shown, representing the highest and lowest percentage of homes where electrification is technically possible, fewer than 20% of feeders need to be treated to electrify 50% of off gas grid housing. On the 1-in-20 peak winter day (Figure 14), where ASHPs are augmented with direct electric heater back-ups over 40% of feeders need to be treated to reach 50% electrification and the overall percentage of homes that can be electrified within current network capacity plateaus at 60%, 30% lower than in the average peak winter day scenario.

average peak winter day scenario.

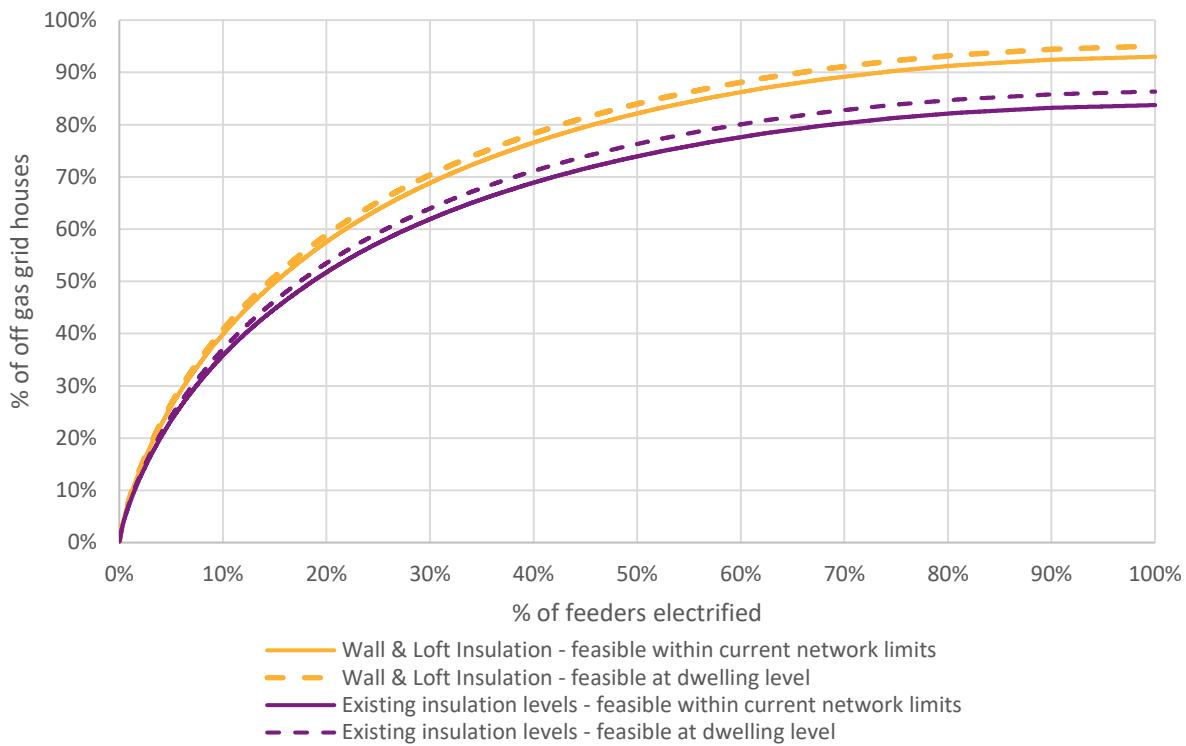


Figure 13: Potential to electrify off gas grid houses at the dwelling level and at the network level within current network limits at current insulation levels and at the best insulation scenario (wall & loft insulation) on an average peak winter day.

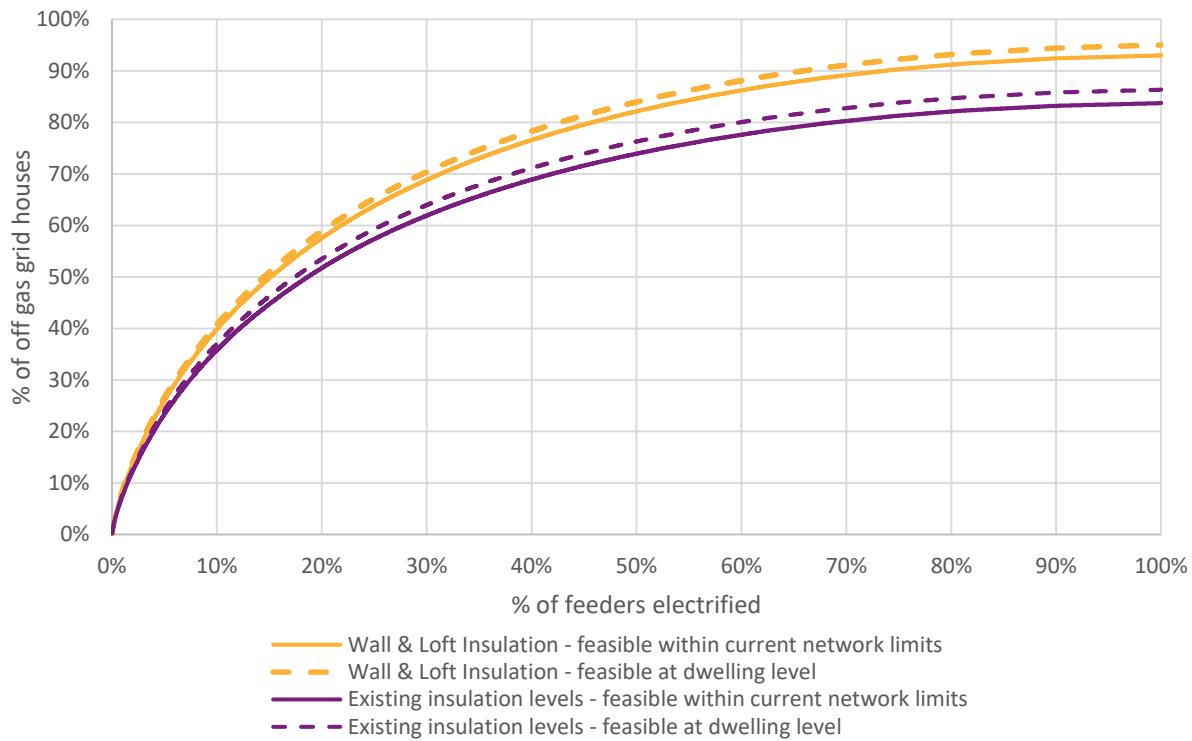


Figure 14: Potential to electrify off gas grid houses at the dwelling level and at the network level within current network limits at current insulation levels and at the best insulation scenario (wall & loft insulation) on a 1-in-20 peak winter day (ASHP with back up electric).

Air source heat pumps preferred merit order

The deployment of LT ASHPs dominates the technology mix in this scenario, making up between 58% and 77% of dwelling heating systems, as shown in Table 6.

Table 6: Deployment of technologies in the Current Installation Preference scenario

% of dwellings	Electric heating only	Loft insulation	Wall & Loft Insulation	Floor & Loft Insulation
HT ASHP	7%	4%	0%	2%
LT ASHP	58%	66%	77%	71%
HT GSHP	2%	0%	0%	0%
LT GSHP	6%	6%	3%	5%
Direct electric	0%	0%	0%	0%
New storage heaters	13%	13%	14%	13%
Existing storage heaters	1%	1%	0%	0%
Non-electric	14%	10%	5%	8%

In this scenario, as shown in Table 7, the percentage of feeders overloaded is approximately double those observed in the energy saving merit order scenario for all insulation levels.

Table 7: Proportion of households that can have electric heating fitted considering low voltage network constraints (Air source heat pump merit order scenario – ASHPs are prioritised over GSHPs)

Scenario	% of dwellings with electric heating	Increase in peak load (kW/dwelling)	% of feeders with overloaded	% of dwellings that could be electrified within feeder limits
Current state				
Average peak winter day	24%	0	1%	n/a
Existing levels of insulation				
Average peak winter day	86%	3.74	25%	82%
1-in-20 peak winter day - larger ASHP with no back up electric	86%	6.4	62%	46%
1-in-20 peak winter day - ASHP with back up electric	86%	8.04	70%	41%
Loft insulation				
Average peak winter day	90%	3.92	26%	86%
1-in-20 Peak winter day - larger ASHP with no back up electric	90%	6.73	64%	47%
1-in-20 peak winter day - ASHP with back up electric	90%	8.50	71%	41%
Wall & Loft Insulation				
Average peak winter day	95%	3.86	25%	92%
1-in-20 Peak winter day - larger ASHP with no back up electric	95%	6.65	63%	50%
1-in-20 peak winter day - ASHP with back up electric	95%	8.45	71%	43%
Floor & Loft Insulation				
Average peak winter day	92%	3.84	25%	88%
1-in-20 Peak winter day - larger ASHP with no back up electric	92%	6.52	62%	49%
1-in-20 peak winter day - ASHP with back up electric	92%	8.26	70%	42%

The average peak winter day in the current merit order shows similar levels of feeder overload to the 1-in-20 peak winter conditions in the energy saving merit order, with approximately 25% of feeders overloaded in all insulation scenarios, as shown in Figure 15.

Approximately 70% of feeders are overloaded in 1-in-20 peak winter conditions if this technology mix is deployed, reducing the percentage of off gas grid homes that could be electrified to 40%. This is shown in Figure 15 where the majority of the feeders are distributed above 100% utilisation.

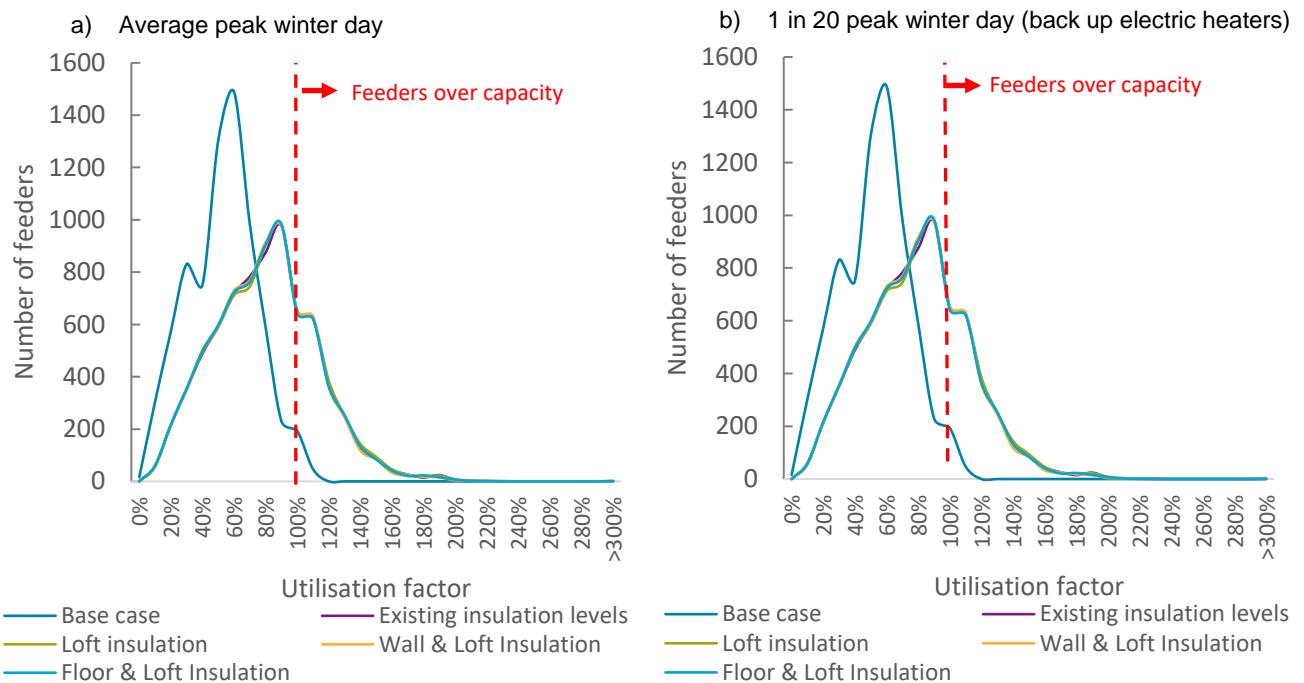


Figure 15: Distribution of feeder utilisations for a) average winter peak scenario, and b) 1-in-20 peak winter day (back up electric heaters) scenarios. Area under curves is proportional to the percentage of feeders overloaded.

6.2 Sensitivity testing

The above results are based on feeders being deemed to be overloaded once their utilisation factor reaches 100%. This leaves no contingency or redundancy in the network and could be seen as a critical risk to network security. Figure 16 shows an additional sensitivity on model outputs for the energy savings merit order, where the threshold for feeder overload has been reduced to a utilisation factor of 90%. The above results are based on feeders being deemed to be overloaded once their utilisation factor reaches 100%. This leaves no contingency or redundancy in the network and could be seen as a critical risk to network security. Figure 16 shows an additional sensitivity on model outputs for the energy savings merit order, where the threshold for feeder overload has been reduced to a utilisation factor of 90%.

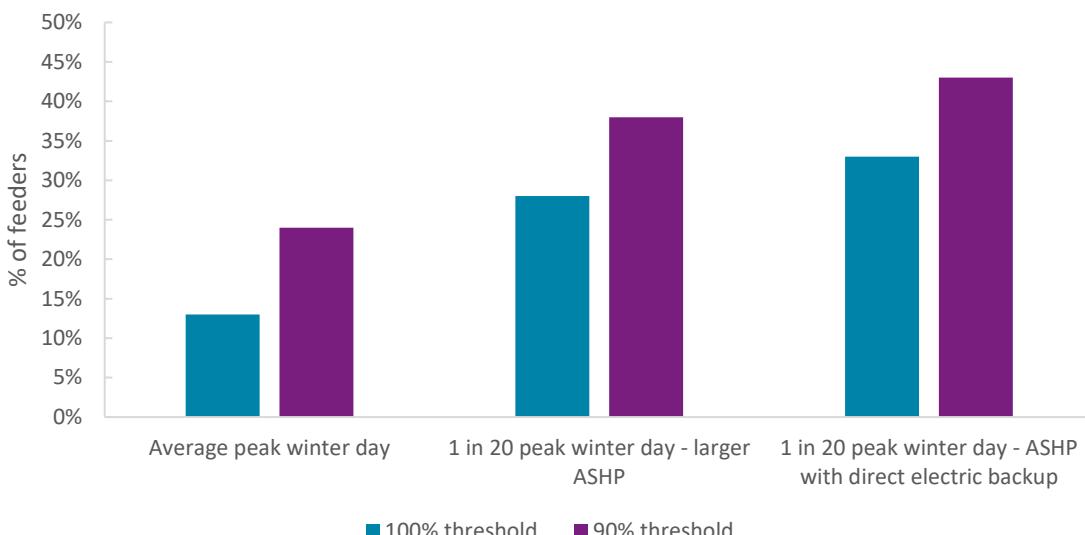


Figure 16: Change in percentage of feeders overloaded when the threshold for feeder overload is reduced to 90% utilisation factor. Results are for the electrification only scenario (i.e. no additional insulation installed).

6.3 Options available to accommodate additional electric heating

This section addresses options available to accommodate additional electrification of heating by enhancing capability of the low voltage electricity distribution network.

There are a wide range of ‘customer side measures’ that could be implemented that will reduce the impact of electrification of heating on the off-gas grid network, as an alternative to conventional reinforcement. The impact of these measures has been previously modelled by ENWL and Delta Energy & Environment¹⁹ and their findings are summarised below, grouped into five core themes.

- More efficient electric heating through increasing heat pump efficiency:** Heat pumps today vary in efficiency (COP), with more expensive heat pumps typically being more efficient. An average reduction of 0.6 kW per dwelling (approximately 20% of peak heating demand), can be achieved by increasing HP efficiency, assuming a 0.75 improvement in COP in HT HPs and 0.5 improvement in COP in LT HPs) on most days.
- Increase heat pump capacity to allow 1-in-20 peak load to be met through heat pump operation alone, reducing use of direct electric back up.** A significant proportion of heat pumps today are typically sized to meet 90 – 95% of the heat load on the coldest days of the year, with a backup electric heater being used (only on the coldest days) to meet the peak heat loss²⁰. This reduces the capacity of the heat pump required, lowering the upfront cost faced by customers, but increases the electricity demand on the network on the coldest days of the year. For example, peak electrical load per household can nominally be reduced by 1 – 2 kW (electrical) by increasing the heat pump size from 6.5 kW to 7.5 – 8.5 kW (thermal output).
- Shift the demand for peak heat using smart controls.** Control strategies could include:

¹⁹ The findings in each of the five core themes presented reference the Delta-ee report presented for ENWL (2016), *Managing the future network impact of electrification of heat*, <https://www.enwl.co.uk/globalassets/innovation/enwl001-demand-scenarios--atlas/enwl001-closedown-report/appendix-2---delta-ee---managing-future-network-impact-of-electrification-of-heat.pdf>

²⁰ Delta-ee insight based on information from installers

- a. Better control of the heat pump to provide 'smoother' operation by stopping the heat pump cycling on and off less
- b. Pre-heating to reduce the maximum load
- c. Pre-heating to bring forward the max. load
- d. Over-heating to smooth the peak
- e. Wider comfort band
- f. Community control strategies to optimise the timing of demand across a feeder, maximising diversity.

Use of smart controls by DNOs to reduce heating load in peak times has been trialled in the UK by the Customer-Led Network Revolution project²¹. This study showed that smart controls that could respond to a DNO signal to turn off heat pump load were technically successful at removing heat pump driven electricity load during peak times. However, a significant rebound effect was observed in the time periods following the turn-off, indicating that further refinement of these controls could be beneficial.

4. **Shift the demand for peak heat using thermal energy storage:** Improved control strategies using smarter heating/heat pump controls in combination with thermal storage in the form of a buffer tank could play a sizeable role in shifting peak electricity demand. If a buffer tank were installed alongside every heat pump, the heating demand could be met at peaks times by the buffer tank rather than the heat pump. The heat pump could then charge the buffer tank (and pre-heat the house) during times of lower demand. An expensive & potentially challenging customer side measure to introduce – but the avoided network costs are predicted to be significant, with a reduction in peak load of 2 kW (approximately 70%) in peak load per dwelling.
5. **Shift demand for peak heat using electrical battery storage.** Battery storage is increasingly being adopted in the residential sector and could play a sizeable role in shifting peak electricity demand. If a battery storage system were installed alongside every heat pump, the electricity demand of the heat pump could be met at peak times by the battery rather than the grid. The battery could then charge during off-peak/period of lower demand. This could yield a 2kW (approx. 70%) reduction in peak load per household.

Theoretically, the above measures could enable heating load to become completely flexible, leading to a flat electricity demand profile instead of causing significant peaks. However, this is likely to come at significant capital cost for customers and is unlikely to occur without financial or regulatory intervention. Since these are outside of scope of this project, a high-level approach has instead been taken to identifying the impact that implementing these solutions has on the network.

Figure 17 and Table 8 show the impact a 20%, 50% and 70% reduction in peak load has on the percentage of low voltage feeders overloaded, which could be achieved through a combination of the measures described above.

A reduction in peak load of 70%, possible through measures such as thermal or electrical energy storage combined with smart controls, could reduce the percentage of feeders needing reinforcement from ~43% on a 1-in-20 peak winter day to under ~10%. However, these measures come at significant capital cost for residents and a cost benefit analysis should be performed comparing this solution to the cost of network reinforcement.

²¹ Customer-Led Network Revolution (2015), *Insight Report: Domestic Direct Control Trials (CLNR L096)*, <http://www.networkrevolution.co.uk/project-library/insight-report-domestic-direct-control-trials/>

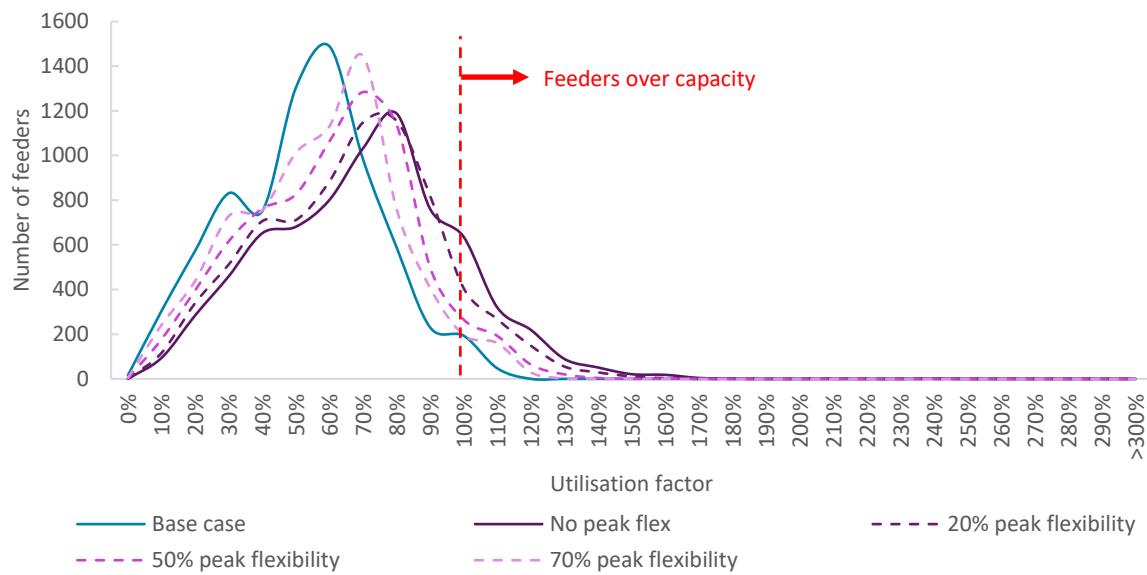


Figure 17: Change in distribution of off gas grid feeder utilisation factors with varying levels of peak load flexibility for the electric heating only scenario on an 'average' peak winter day.

Table 8: Impact of flexible peak load scenarios on percentage of feeders overloaded and percentage of dwellings that could be electrified within current feeder limits.

Scenario	% of feeders with overloaded				% of dwellings that could be electrified within feeder limits			
	0%	20%	50%	70%	0%	20%	50%	70%
Flexibility scenario								
Current state								
Average peak winter day	1%	1%	1%	1%	n/a	n/a	n/a	n/a
Existing levels of insulation								
Average peak winter day	13%	9%	6%	4%	84%	84%	85%	85%
1-in-20 peak winter day - larger ASHP with no back up electric	28%	20%	11%	6%	67%	71%	77%	80%
1-in-20 peak winter day - ASHP with back up electric	33%	27%	14%	7%	64%	68%	75%	79%
Loft insulation								
Average peak winter day	12%	9%	5%	4%	88%	88%	88%	88%
1-in-20 Peak winter day - larger ASHP with no back up electric	28%	21%	11%	6%	70%	74%	80%	83%
1-in-20 peak winter day - ASHP with back up electric	33%	27%	14%	7%	66%	71%	78%	82%
Wall & Loft Insulation								
Average peak winter day	10%	8%	5%	4%	93%	93%	93%	93%
1-in-20 Peak winter day - larger ASHP with no back up electric	27%	19%	10%	6%	75%	79%	85%	88%
1-in-20 peak winter day - ASHP with back up electric	32%	26%	13%	7%	71%	76%	83%	87%
Floor & Loft insulation								
Average peak winter day	12%	8%	5%	4%	89%	90%	90%	90%
1-in-20 Peak winter day - larger ASHP with no back up electric	27%	20%	11%	6%	72%	76%	82%	85%
1-in-20 peak winter day - ASHP with back up electric	33%	27%	14%	7%	68%	73%	80%	84%

7 Conclusions

The purpose of this report was to provide a high-level estimate for the number of off-gas grid dwellings in which it is technically feasible to install a heat pump based on household thermal and practical constraints as well as wider low voltage distribution network constraints. The conclusions below address the research questions outlined in Section 2.2.

7.1 Heating systems suitability

Considering only technical suitability with no additional insulation improvements (and excluding practical installation limitations), **91% of homes are suitable for some form of electric heating system** in their current state. The largest proportion of homes are suited to HT-GSHPs at 82% and direct electric heating is suitable to the smallest number of homes at 52%. If additional insulation measures are considered, the combination of wall & loft insulation results in the largest reduction of heat loss. **If all suitable homes are fitted with wall & loft insulation, 97% of homes are suitable for at least one type of electric heating system.** With loft insulation only and loft & floor insulation only this number falls to 94% and 95% of homes, respectively.

The energy savings achieved compared to the incumbent system is heavily dependent of the house type. The largest energy savings, across the different technology types and insulation levels, are achieved for detached homes. The low temperature GSHP, across all house types, achieves the largest overall energy savings. The annual energy savings for detached homes is in the range of 14,000 kWh - 17,500kWh across the different insulation scenarios. In detached homes, direct electric heating achieves the lowest over all energy savings, in the range of 2,700 kWh – 6,500 kWh across the different insulation scenarios. Across all the heat pump types fitted in both semi-detached and terraced houses energy savings in the range 6,000 kWh - 10,700 kWh are achieved. The savings achieved by direct electric heating and storage heaters are broadly similar for semi-detached and terraced homes and are in the range of 1,400 kWh – 5,000 kWh across the different insulation scenarios. It is important to note, that these values compare end use energy and not primary energy, therefore electricity generation efficiency is not included.

Based on a sensitivity analysis around some of the key inputs to the model, **the heating circuit flow temperature and the treatment of using the ‘proceed’ vs ‘proceed & caution’ decisions (as per heat emitter guide) have the largest impact on the technical feasibility of electric heating.** A 5°C decrease in flow temperature results in 8.4% fewer homes being suited to at least one type of electric heating system in the case of no additional insulation having been added. In the wall & loft insulation scenario 2.7% fewer homes are suited to at least one type of electric heating system. Similar results are observed when it is assumed only homes meeting the ‘proceed’ criteria (rather than ‘proced & caution’) of the heat emitter guide are suitable for a heat pump. Increasing the current (amps per phase) available for electric hating to 60A (from 40A) increases the number of suitable homes by 4.4% in the case when no additional insulation is considered.

If practical feasibility constraints are considered 86% of homes are suitable for at least one type of electric heating system (with no additional insulation). If wall & loft insulation is fitted then this rises to 95% suitability of off-gas grid homes. When considering the technologies individually, the largest proportion of homes are suited to high temperature ASHPs at 60% and low temperature GSHPs heating is suitable to the fewest number of homes at 44%.

For the **retrofit installation of low temperature heat pumps, in >80% of cases the existing radiators will need to be replaced.** In the case of **high temperature heat pump installation approximately 25% of the existing radiators will need to be replaced.**

7.2 Network impact of electrification of off gas grid heating

In the baseline electric heating only scenario (no additional insulation), **84% of homes can be electrified on an average peak winter day, assuming the installation of GSHPs takes preference over ASHPs. This falls to 64% of homes if a 1-in-20 peak winter scenario is assumed.** In the case that all suitable homes have **loft & wall insulation installed**, the number of **homes than can be electrified, on an average winter day goes up to 93%**. Even with these additional insulation measures, during a 1-in-20 winter peak scenario this drops to ~71% of homes.

Assuming **ASHPs are the preferred heating technology**, in the baseline electric heating only scenario, **82% of homes can be electrified on an average peak winter day.** This falls to **41% of homes if a 1-in-20 peak winter scenario is assumed.** In the case that all suitable homes have loft & wall insulation installed, the number of homes than can be electrified goes up from 82% to 92% on an average peak winter day. However, even with these additional insulation measures, during a 1-in-20 winter peak scenario this drops to a similar level as the baseline electric heating only scenario, at approximately 43% of homes.

There are several options available to reduce the peak demand due to electric heating on the LV network. These include improving the efficiency of heat pumps, especially under cold weather operation regimes, increasing heat pump capacity to meet the 1-in-20 peak load without the need for additional direct electric heating, or optimised operation to reduce heat pump cycling and peak shifting using smart controls and/or thermal stores or battery storage. **A reduction in peak load of 70%, through a combination of the aforementioned measures, could reduce the percentage of feeders needing reinforcement from ~30% on a 1-in-20 peak winter day to under ~10%.**

Acknowledgements

Delta-ee would like to thank the following DNOs who supplied us with data and/or helped contribute to our further understanding of low voltage distribution networks (in alphabetical order):

- Electricity North West limited
- Northern Powergrid
- Scottish and Southern Electricity Networks (SSE)
- UK Power Networks
- Western Power Distribution

Delta-ee would also like to thank the heat pumps installers and design engineers, along with their associated companies that assisted with this work.

8 Appendix A – heating system suitability

8.1 Archetypes used

Splitting the housing stock into different archetypes provides a mechanism to identify type of houses that are technically suitable for different electric heating technologies versus those that are not. In addition, identifying technical feasibility, archetypes also allow for a better understanding of the practical feasibility regarding the use of different heating technologies.

The archetype analysis makes use of two primary qualifying criteria:

- Is the primary heating fuel gas? [Yes = FAIL, No = PASS]
- Is the dwelling located in an urban location? [Yes = FAIL, No = PASS]
- Is the dwelling a flat? [Yes = FAIL, No = PASS]

BEIS assumed that flats would be the main category of dwellings which are urban but not gas heated, and therefore separately excluded only urban electrically heated flats. As the scope defines “rural off-gas grid dwellings”, we intend to exclude all urban dwellings.

The available EHS 2011 data provides an indication of the rurality of dwellings. Figure 18 shows homes split by dwelling type and rurality indicator, for houses which have passed the first gateway question (“Is the primary heating fuel gas?”). We have chosen to define both ‘rural’ and ‘village’ in our definition of “rural off-gas grid dwellings”.

Due to the unavailability of the rurality indicator for the 2016 data, it is not possible to apply the stage 2 gateway question to our most up to date data. In the absence of this data, we have used the following two steps:

- All flats are excluded from analysis (therefore creating the third gateway question): 2011 data identifies only 2% of non-gas heated houses as being rural or in a village as shown in Figure 18 (2% of purpose built low rise flats, 0% of purpose built high rise flats, 5% of converted flats). Scaling 2016 numbers to 2011 data in the CHM with such low numbers of applicable flats is not deemed to be sufficiently accurate to give meaningful results.
- All houses in the 2016 data are scaled to the proportion of rural/village houses in the 2011 data, within each archetype.

For example: for a specific archetype, if the 2011 data had a weighted dwellings number of 8,000 dwellings represented, of which 2,000 are urban/town, this leaves 75% of that archetype as rural/village dwellings. If the 2016 data has a weighted dwellings number of 10,000 dwellings represented by that archetype, this will be scaled down by 75% to 7,500 dwellings represented by that archetype and 7,500 dwellings will be the number used in the modelling. This process is described further in section 8.2

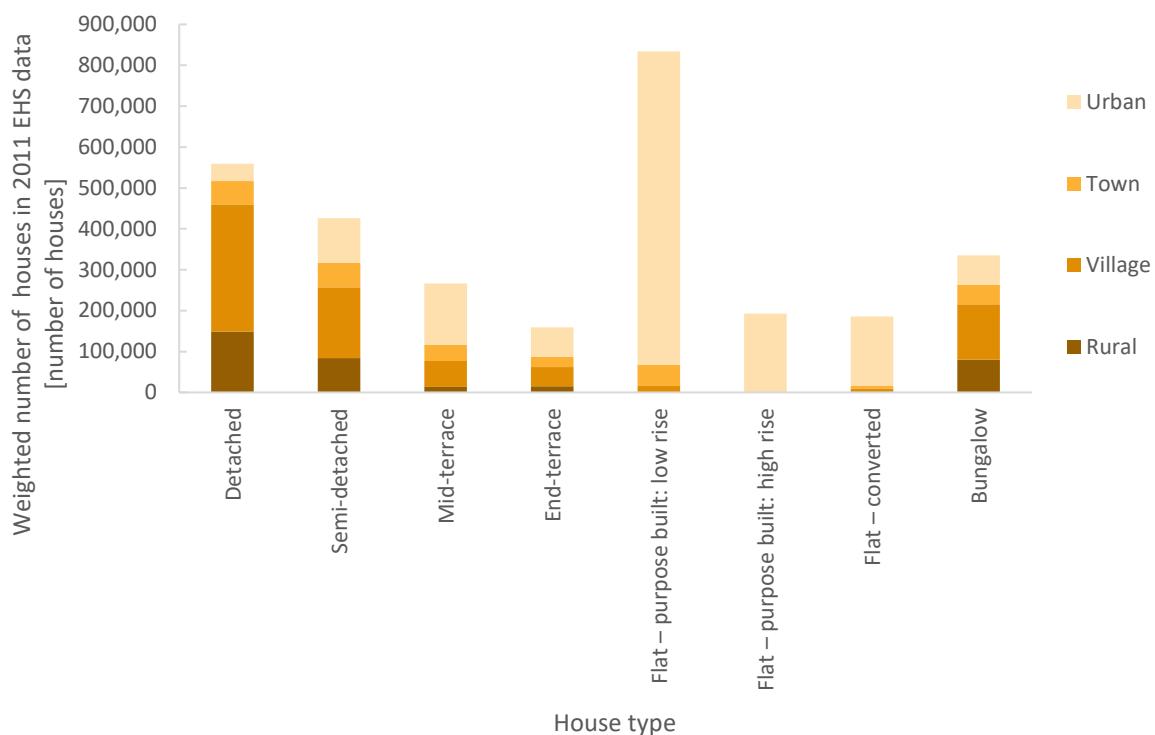


Figure 18: How defining the line of rurality affects the number of off-gas grid dwellings

After applying the qualifying criteria above, Table 9 below outlines the factors used to segment the building stock into the different archetypes.

Table 9: Segmentations made to create the archetypes

House Type	Heating Type	Wall Type	Loft Ins. Level	House size
Detached	Oil	Insulated	$\leq 50\text{mm}$	$\leq 120\text{m}^2$
Semi-Detached	Electricity	Uninsulated Cavity	50mm - 150mm	$> 120\text{m}^2$
Mid-Terrace & End-Terrace	Solid & Other	Uninsulated Solid	$> 149\text{mm}$	

Table 9 results in a possible total of 216 archetypes. Based on 2016 English Housing Survey data and 2008 LiW data (scaled to 2016 insulation levels) this results in a total of 110 non-zero archetypes.

We see the use of archetypes as important for the following purposes:

- To present the spread of UK houses in a clear way which is not dependent on those houses sampled within each year of EHS
- To provide a framework for comparison of data sets between 2011 data (within the Cambridge Housing Model) and most recent data (2016 EHS data).

The sections below justify the inclusion of each of the above five categories and the reasoning behind specific breakdown of each category. Age was not considered as a separate category as the main effect of house age is on the building fabric and level of insulation and these variables are sufficiently covered by the wall type and loft insulation characteristics.

Justification of house type category

House type is considered as being an important factor in the archetype break down for comparison between 2011 and 2016 data sets. We expect that suitability of heating systems will vary across the different house types due to factors such as exposed wall area and trends of typical house sizes. House type is also a relevant indicator regarding the practicality of heat pumps, which is taken into consideration after the initial technical feasibility modelling stage.

In this analysis end-terrace houses have been grouped with mid-terraced houses due to the following reasons:

- In our approach, thermal modelling on houses is being used at a more granular level; rather than one thermal model run per archetype, each house in the EHS sample is modelled separately. We deem that the heat loss of the house will be more heavily dependent on the type of wall, loft insulation, and floor area, and therefore the grouping of houses by number external walls is not necessary.
- As part of our analysis, we use the archetypes to make judgements of practicality for heat pump installations. We surmise that there are greater similarities between end-terrace houses with mid-terrace houses than with semi-detached houses, and therefore find this a more useful grouping.

Bungalows were not included as a separate house type category as they are not included in the LiW data (as described further in section 8.2).

Justification of heating type category

Heating system was identified as an important factor in dividing house archetypes based on previous work completed by Delta-ee²². It is expected that different energy savings will be achieved by an electric heating system compared to the incumbent heating system. In some cases, the incumbent system may also yield additional insight into the practicality of homes for heat pumps, and in particular which homes would need additional heat distribution equipment to be installed.

Justification of wall type category

Wall type has been included as it gives a key metric for comparing the 2011 and 2016 EHS data. It also separates out the houses with insulation potential, considered separately in the second phase of modelling. The BEIS 2018 NEED data²³ indicates that significant energy savings, on the order of 12% (mean), can be achieved using solid wall insulation, and showing the increased technical viability of different electric heating technologies with accompanying efficiency improvements is an important output from this analysis.

In analysing the data, both the 2011 and 2016 EHS data contains houses which do not have conventional solid or cavity brick walls. Of the 2011 EHS off-gas grid houses, 31 are non-masonry construction and split by 21 timber frame and 10 system-built. A breakdown of type of 'other' walls is not available in the 2016 EHS data. Both have construction characteristics best matched to solid wall houses, and the challenges for insulating these wall types are more like those of solid wall properties than cavity wall properties. Therefore, the 20 dwellings in the 2016 data set with wall construction classed as 'other' will be classed as solid wall properties with no further improvement potential.

²² Based on work completed by Delta-ee (2018). Project: *Energy System Catapult: Carbon Targets*. Issued to internal BEIS team 16/07/18

²³ BEIS 2018 National Energy Efficiency Data (NEED) Framework - Summary of analysis using the National Energy Efficiency Data Framework, Table 4.1

Justification of loft insulation level category

In previous modelling by BEIS, loft insulation was used to divide houses into archetypes, providing two divisions: $\leq 150\text{mm}$ and $> 150\text{mm}$. There is a large variation in heat loss that occurs in the $< 150\text{mm}$ loft insulation band, and therefore breaking this band into two smaller bands is more suitable. To assess at what existing insulation thickness the division of the band should be, we have considered the energy savings provided by loft insulation using the CHM.

To calculate energy saving,

- each off-gas grid house was run in the CHM in its current state,
- then each house had insulation upgraded to current building standard levels (typically to 250mm by changing the insulation code to 9 as described in section 8.4)
- The energy saving was the difference between these two values for each house in the CHM

Figure 19 shows the energy savings categorised by the initial level of loft insulation. The central point shows average energy savings at each initial level of loft insulation and the yellow bars show the range between the 10th and 90th percentile of houses at each initial level of loft insulation

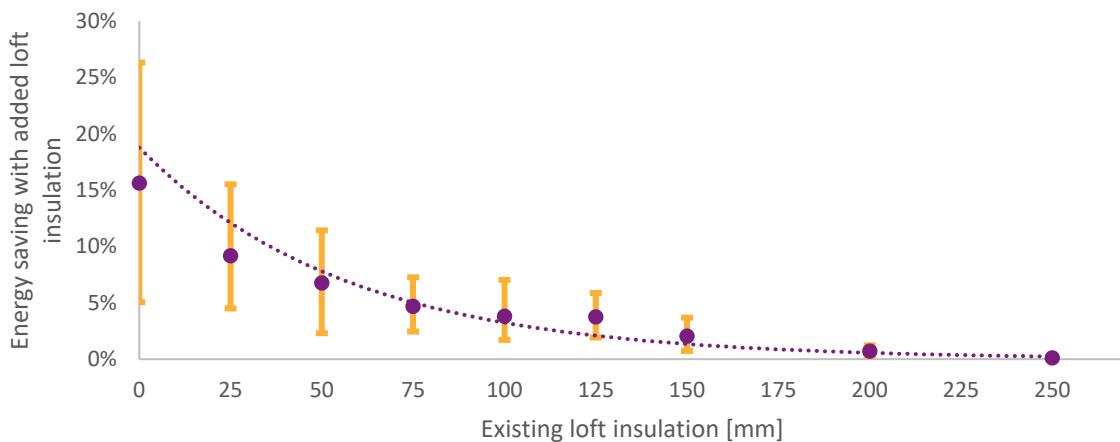


Figure 19: Exploring where to put the cut off in the 'high' and 'low' loft insulation bands – energy saving versus loft insulation thickness. The purple circles show the average energy savings at each initial level of loft insulation and the yellow bars show the range between the 10th and 90th percentile of houses at each initial level of loft insulation. Graph based on outputs from the CHM for the current work.

Energy savings from loft insulation are a proxy for heat loss through the loft in the existing state. Figure 19 confirms that there is large variation between 0 and 150mm of existing insulation, and therefore justifies our intention of dividing this segment into two bands. A 50mm insulation level has been chosen as the dividing point as above 50mm of insulation only 5% or less energy savings are achieved by adding additional insulation. At insulation levels below 50mm, the energy savings (or heat loss through the roof) grow exponentially and there are therefore significant energy saving opportunities.

Having removed flats from the analysis (as explained above), there are no longer any dwellings without a roof, and therefore this category is no longer required in the archetype definition.

Justification of house size category

House size was identified as an important factor in dividing house archetypes in previous analysis based on previous work completed by Delta-ee²⁴, as energy demand scales strongly with floor area. The division between small and large houses was put at 120m² as below this size are the majority of houses (80%) and in the >120m² band house size can grow exceptionally large, having a large effect on the energy demand calculations. Most houses greater than 120 m² floor area are detached, and therefore this division is expected to be most significant for these detached houses.

8.2 Scaling housing data to 2016 figures

The CHM (v3.02) is at the core of the approach being used, but the data within the CHM is based on 2011 EHS data. In order that the results represent the current housing stock as well as possible, adjustments are made to the stock data in the CHM to scale the housing stock data up to 2016 stock data.

England

The weighting factors for rural off-gas grid houses in England are derived from EHS 2016 data. However, two key pieces of information are missing which make this more challenging:

- EHS 2016 data does not contain indicator of whether house is in a rural or urban location, preventing the “Is the dwelling located in an urban location?” qualifying criteria from being applied.
- Bungalows are listed only as bungalows, and not also as an equivalent descriptor.²⁵

To estimate the houses which are rural, a three-step approach was taken:

- 1) all flats removed from analysis: this decision was justified in section 8.1 above (only 2% of non-gas heated houses in EHS 2011 data are listed as being rural or in a village).
- 2) For the remaining houses, the ratio of rural to urban houses within each archetype within the EHS 2011 data set was applied to the EHS 2016.
- 3) Where all houses within an archetype in the EHS 2011 data set are urban, and there are no rural houses in the LiW dataset in that archetype, all houses in that archetype in the EHS 2016 data set are assumed to be urban and removed.
- 4) Where all houses within an archetype in the EHS 2011 data set are urban, but there are rural houses in the LiW dataset in that archetype, all houses in that archetype in the EHS 2016 data set are assumed to be rural and those CHM houses are retained.

To approximate bungalows to other house types, the following approach was taken based on analysis of the EHS 2011 data set:

- Bungalows with floor area greater than 70 m²: allocated as detached houses (in EHS 2011 data set 88% of bungalows with floor area $\geq 70\text{m}^2$ are detached).

²⁴ Based on work completed by Delta-ee (2018). Project: *Energy System Catapult: Carbon Targets*. Issued to internal BEIS team 16/07/18

²⁵ In the EHS 2011, two different house type categorisations are listed, one of which includes bungalow as a value (dwelling type: dwtypenx) and one which doesn't (dwelling type: dwtype7x); from this, a semi-detached bungalow could be identified as such. In the LiW data, no houses are listed as bungalows (a semi-detached bungalow would be listed as semi-detached), whereas in the EHS 2016 data, the dwelling type: dwtype7x definition is not included (semi-detached bungalow listed as bungalow). Therefore, consolidation of data requires one approach to be used, and it has been decided that we will not include bungalows as a separate descriptor (a semi-detached bungalow is to be listed as semi-detached), and therefore EHS 2016 data requires adjustment.

- Bungalows with floor area less than 70 m²: split evenly between terraced houses and semi-detached houses (in EHS 2011 data set bungalows with floor area < 70m² are 42% terraced and 39% semi-detached).

Wales

The weighting factors for rural off-gas grid houses in Wales are derived from LiW 2008 data. To modernise the numbers to better reflect current housing stock, the assumption has been made that houses in Wales have improved in efficiency at the same rate as houses in England. Therefore, a three-step process was used:

- 1) Archetypes were split according to those criteria which remain unchanged (house type, house size, heating fuel) and those which could have changed in time (loft insulation level, wall insulation). This meant that across each of the fixed archetypes, the migration of houses from low insulation to higher insulation over time can be assessed
- 2) EHS 2008 data was compared to EHS 2016 data, and the percentage improvements of houses recorded
- 3) The same improvements were applied to LiW 2008 data to approximate a LiW 2016 data set

For wall insulation, the proportion of houses with each level of insulation was quite similar between LiW 2008 data and EHS 2008 data, therefore applying the same improvement to the LiW 2008 data as was seen across the EHS data was deemed a good approximation. This process is shown in Figure 20.

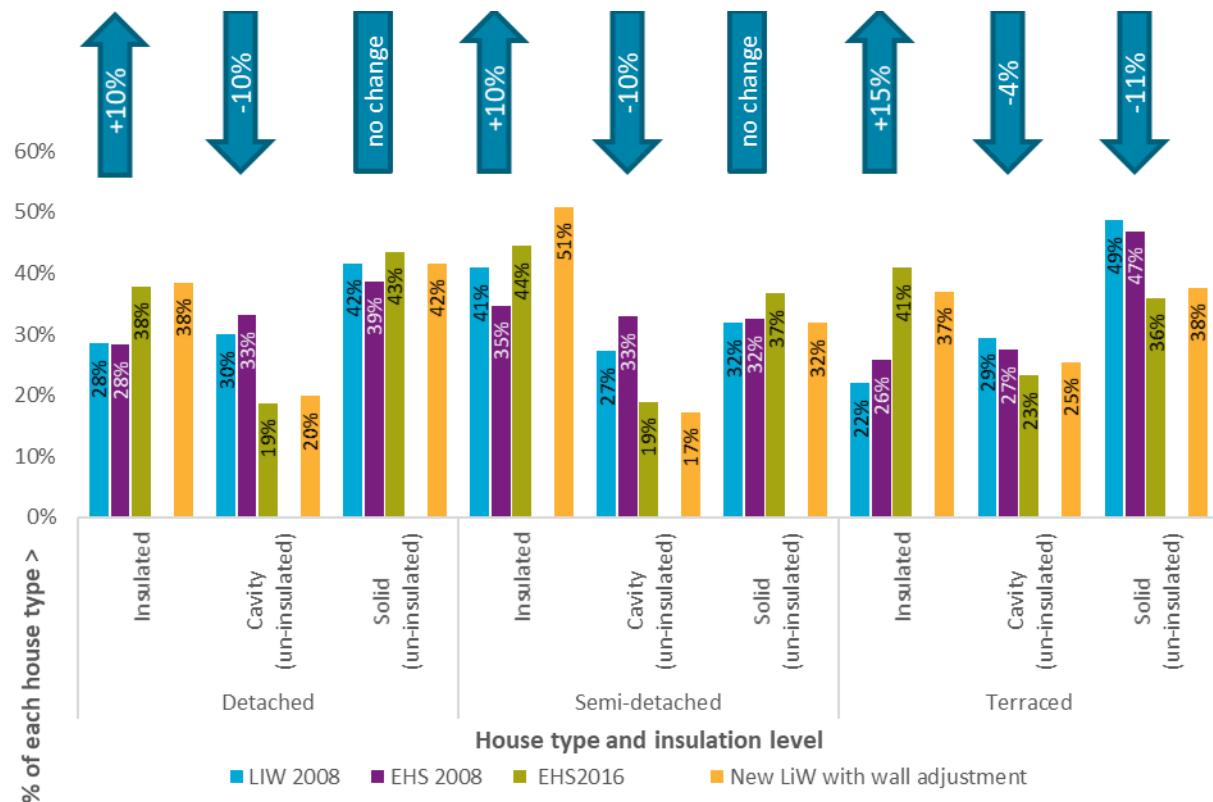


Figure 20: Comparison of wall insulation levels across each house type in Living in Wales (LiW) 2008 data set, English Housing Survey (EHS) 2008 data set and EHS 2016 data set. Blue arrows at the top of the figure show the adjustment to be applied to the LiW data set and the orange bar is the new values of the LiW data revised to 2016 levels based on this wall adjustment.

All insulated walls were assumed to have loft insulated at the same time, therefore affecting the proportions of loft insulation figures. For loft insulation, the LiW and EHS data was not very similar,

therefore in some cases the LiW data was increased to the same percentage in 2016 and sometimes increased by the same amount as have happened across the EHS data.

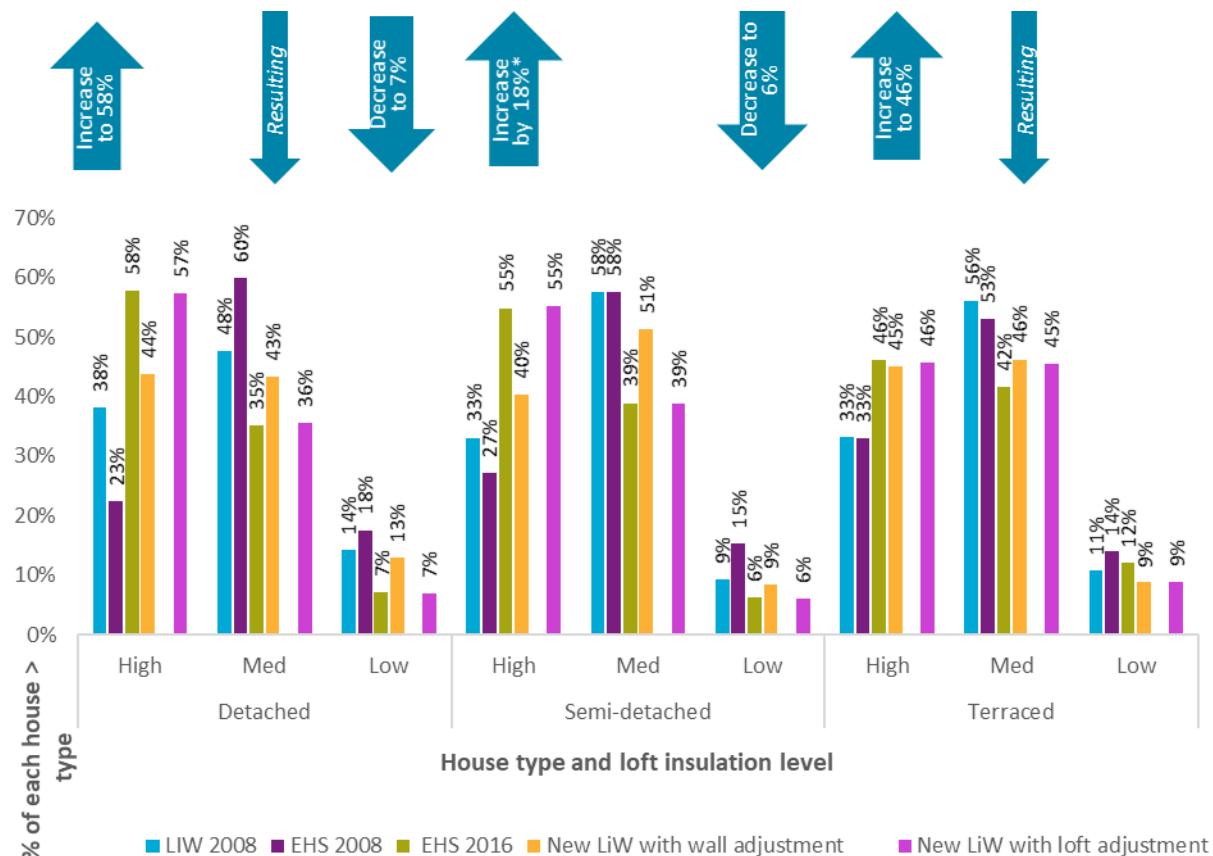


Figure 21: Comparison of wall insulation levels across each house type in Living in Wales (LiW) 2008 data set, English Housing Survey (EHS) 2008 data set and EHS 2016 data set. Blue arrows at the top of the figure show the adjustment to be applied.

The number of houses in each archetype is used to scale the weighting factors for each CHM house:

- For archetypes which are non-zero in both 2011 and 2016 EHS data sets, a scaling factor is used to upgrade the data in the CHM (2011 data) to the 2016 data.
- For archetypes which are zero in 2011 EHS but non-zero in 2016 EHS, one or more new house definitions are created in the CHM to represent these houses. The new house definitions are based on existing house definitions from 2011 data, which are of the closest archetype, all of which can be satisfied by using a house definition with a different level of loft insulation and changing the value of loft insulation as input to the model.

The number of archetypes these approaches are applicable to are shown in Table 10.

Table 10: Break down of number of non-zero archetypes in 2016 and 2011 data, and method for upgrading CHM to represent 2016 data

	Number of archetypes	Represented number of dwellings in England and Wales (2016 data)	Approach to match 2016 data to CHM
Total number of archetypes	216		
Archetypes which are non-zero in 2016 compiled data	110	1,309,187	
Archetypes which are non-zero in both 2011 and 2016 data	102	1,268,434 (97%)	Number of represented dwellings are scaled using a scaling factor
Archetypes which are non-zero in 2016 data but zero in 2011 data	18	40,754 (3%)	New dwelling definition required in CHM for this archetype

8.3 Heat pump electrical requirements

Once the heat loss of the different dwellings has been calculated, the electrical requirement to meet that thermal loss for the different technologies is calculated. For heat pumps, the efficiencies have been calculated in the following ways:

Calculation of COPs for the electric heating system suitability model

Low temperature heat pump COPs have been calculated based on manufacturer datasheets. To obtain the 'worst-case' COPs, the maximum operational current rating (this is not to be confused with the fuse rating, which in all cases is higher than the maximum current rating) of various heat pumps was converted to a kilowatt rating (by multiplying by 230 volts; e.g. 13A x 230V = 3kW). The COP was then calculated as the maximum heat pump output (e.g. 6kW thermal output) divided by the equivalent maximum power draw (e.g. 6kW thermal / 3kW max current draw = 2.0 COP). The maximum current draw is excluding any immersion or booster heaters, as the heat pump is assumed to have been correctly sized without the need for supplementary direct electric heating. Worst-case COPs were used to assess the highest possible power demand of the heat pump.

The high temperature heat pump COPs were calculated based on the ratio of low to high temperature COPs reported in a previous BEIS report²⁶. The ratio was applied to the low temperature COPs calculated using the manufacturer heat pump data. Table 11 presents the COPs calculated using this method.

²⁶ BEIS 2016, *Evidence gathering – Low Carbon Heating Technologies Domestic High Temperature Heat Pumps*.

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/565248/Heat_Pumps_Combined_Summary_report_-FINAL.pdf [accessed 15/08/2018]

Table 11: COPs used in the model

Heat Pump Type	Worst case COP
Low-Temperature ASHP	1.65
High-Temperature ASHP	1.45
Low-Temperature GSHP	2.33
High-Temperature GSHP	1.70

In most cases the ‘worst-case’ COP calculated using this method is significantly lower than manufacturer reported COP. Many industry experts agree that the in-situ performance of heat pumps is often below the manufacturer reported data, with the latter measured under ideal steady-state, laboratory conditions and practically difficult to achieve under in situ^{27,28,29,30}. This statement is corroborated by the much lower in situ SPFs achieved in heat pump trials, as compared to manufacturer / energy label SPFs. The COPs reported in Table 11 will also help provide a conservative assessment of the maximum electric demand of the heat pumps in very cold weather.

Calculation of SPFs for the electric heating system suitability model

The low temperature heat pump SPFs were calculated using the 2017 *Detailed analysis of data from heat pumps installed via the Renewable Heat Premium Payment Scheme (RHPP)* study carried out for BEIS³¹. The RHPP ‘B2 cropped dataset’ was used in this analysis, with the cropped dataset having been subjected to several sense checks to exclude anomalous performance and faulty recording equipment. The SPF2 value was used to exclude any effects of immersion heaters / domestic hot water heating and any heat loss from the hot water cylinder. The SPF2 values for the relevant space heating circuit flow temperatures were compared to the average SPFs reported for all heat pumps of the relevant type in the MCS database. The 99th percentile flow temperature values were used to assess the maximum design flow circuit temperature, rather than the average flow temperature which would include the effects of weather compensation. By comparing the average reported MCS SPF at each flow temperature to the RHPP trial data, an average de-rating factor was calculated. This was done using all data points from the RHPP trial data. This de-rating factor was then applied to the relevant MCS SPF at the applicable flow temperature to obtain a measure of the in-situ heat pump performance.

The high temperature heat pumps SPFs were calculated using the same derating factor as calculated for the low temperature heat pumps applied to the high temperature heat pumps in the MCS database. Table 12 presents the SPFs calculated using this method.

²⁷ Delta-ee Expert opinion

²⁸ Toronto Atmospheric Fund 2015, *Global Heat Pump Performance Review for Toronto Atmospheric Fund* <http://taf.ca/wp-content/uploads/2015/06/TAF-Heat-Pumps-Final-Report-2015.pdf>

²⁹ Branka Dimitrijević 2013 *Innovations for Sustainable Building Design and Refurbishment in Scotland*, ISBN 3319024787

³⁰ Staffell et al 2012, *A review of domestic heat pump*, Energy Environ. Sci., 2012, **5**, 9291

³¹ UCL Energy Institute 2017, *Detailed analysis of data from heat pumps installed via the Renewable Heat Premium Payment Scheme*, <https://www.gov.uk/government/publications/detailed-analysis-of-data-from-heat-pumps-installed-via-the-renewable-heat-premium-payment-scheme-rhpp>

Table 12: Seasonal Performance Factors used in the model

Heat Pump Type	SPF
Low-Temperature ASHP	2.83
High-Temperature ASHP	2.19
Low-Temperature GSHP	3.15
High-Temperature GSHP	2.29

8.4 U-values for Insulation

The U-values used for difference insulation levels within the CHM are shown in Table 9.

Table 13: U-values used in Cambridge Housing Model assessment of different levels of insulation improvements

Insulation type	Before insulation		After insulation	
	U-value [W/m ² K]	CHM coding	U-value [W/m ² K]	CHM coding
Cavity wall	1.60 ^a	External wall construction: 9	0.65 ^b	External wall construction: 10
Solid wall (including wall construction defined as "other" with no further description)	1.70 ^c	External wall construction: 3	0.60 ^d	External wall construction: 4
Loft, pitched roof	> 0.16 (0 mm insulation has a U-value of 2.3 W/m ² K)	Loft insulation: <9	0.16	Loft insulation: 9
Room in roof	2.3 – 0.25 (depending on age of house)		0.18	
Floor (all assumed to be solid floor due to no additional information)	0.26		0.20	

^a updated in line with revised values used for solid wall insulation

^{b,d} based on BEIS best practice (already used into CHM)

^c Upper range of value of 1.3 +-0.4 found by Li et al (2015)³²

8.5 Practical suitability of electric heating

For the assessment of the practical suitability of technologies in houses, we have estimated the proportion of houses of each house type that are suitable for each electrical heating system, as shown in Table 14. Estimations are based on a qualitative assessment, and this is matched to a quantitative practical suitability as follows:

- Not practically suitable: 0 %
- Very difficult: 10 %
- Difficult: 25 %
- Moderate: 50 %

³² Li et.al (2015). Solid-wall U-values: heat flux measurements compared with standard assumptions. *Building research & information*. 43(2), p238–252, <http://dx.doi.org/10.1080/09613218.2014.967977>

- Good: 75 %
- Very Good: 90 %
- Excellent: 95 %

The practical factors affecting the adoption of electric heating systems are mainly focussed on the space constraints of a dwelling for fitting in the heat pump units. Internally these are the expander/compressor units, and hot water tanks for delivering domestic hot water. Externally, these are the fan units or ground coils/boreholes (which would require a garden). For direct electric heating and storage heaters, this is available internal wall surface area. In addition to space constraints, aesthetic and noise considerations are considered. Heat pump units are considered by some to be unattractive, especially if they take up a larger space than the heating system they are replacing, and large storage heater units in a living space may be rejected on aesthetic grounds. Finally, practically feasibility also includes a hassle factor which can put off many households from making changes to their home heating system. For example, some households may choose not to adopt direct electric heating or storage heater units if it would require them to rewire a house's internal electricity circuit.

Table 14: Fraction of houses that electric heating systems are expected to be practically suitable for (Adapted from Delta-ee pathways model and updated based on expert opinion)

House Type	Fraction of houses that technology will practically fit into							
	ASHP		GSHP		Direct electric heaters		Storage heaters	
Detached	V. good	90%	Good	75%	Excellent	95%	V. good	90%
Semi-detached	Good	75%	Moderate	50%	Excellent	95%	Good	75%
Terrace	Good	75%	V. difficult	10%	Excellent	95%	Moderate	50%
Flat	Difficult	25%	Zero	0%	Excellent	95%	Moderate	50%
Reasoning	Space needed for outside unit		Space needed for laying coils / digging borehole		Requirement for new wiring (main electricity loop) in older houses		Size is key issue – large units in each room	

9 Appendix B – network modelling

9.1 DNO data cleaning and further assumptions

Data on low voltage transformers and recorded maximum demands were provided by 5 DNOs. This dataset was filtered before use in the model to remove extreme values, such as

- **transformers with utilisation factors of greater than 110%:** the substation might have been used to back-feed another substation suffering an outage at a time of high demand and not be a true indication of the maximum demand on that specific feeder
- **transformers with maximum demand per customers of > 25 kW:** Whilst some of the DNO datasets could be filtered based on customer type, others did not have this information. It has been assumed that transformers with high maximum demands per customer contain industrial and commercial properties, which are out of scope of this analysis.
- **Substations with a rating of less than 15kVA.** a 15kVA is considered the minimum capacity connection required for a household. Transformers with ratings of less than 15kVA were assumed to be serving non-domestic loads such as street lights or traffic lights.
- **Transformers of <20 kVA and greater than 2 customers were removed.** Since 15kVA is considered the minimum suitable capacity for 1 household, any substations with a rating less than 20kVA and more than 2 customers were removed from the dataset. These anomalies are most likely a result of incorrect recording by the technician servicing the substation. This occurs since for pole mounted transformers the technician often estimates the number of customers connected based on a visual inspection rather than verifying the actual number of connections to the transformer. Ground mounted transformers in most cases have much more accurate connected customer data.
- **Blanks, errors and zero maximum demand readings:** these values have been removed as they are assumed to be erroneous readings.

9.2 Calculation of the increase in peak load per dwelling

A step by step example of calculating the increase in peak load per dwelling process is shown for LT ASHPs below.

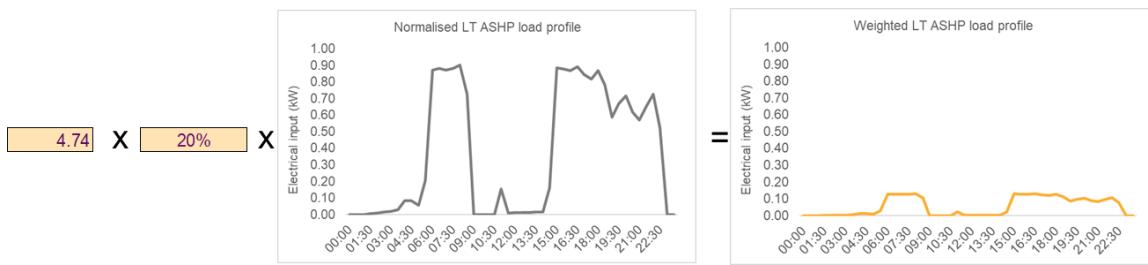
$$1. \sum(\% \text{ of technology in dwelling type}) \times (\% \text{ of dwelling type in off gas grid homes}) = \text{Weighted average \% of technology type in mix of technologies deployed}$$

% of dwelling type heated with LT ASHP		% dwelling type in off gas grid homes		=	20%
Detached - Low	13%	Detached - Low	23%		
Detached - High	6%	Detached - High	35%		
Semi-detached - Low	25%	Semi-detached - Low	9%		
Semi-detached - High	19%	Semi-detached - High	15%		
Terraced - Low	65%	Terraced - Low	7%		
Terraced - High	50%	Terraced - High	11%		

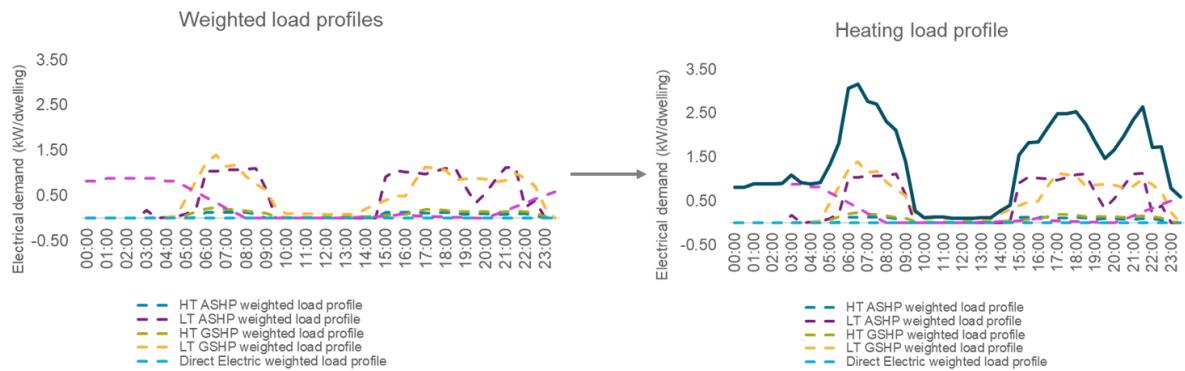
$$2. \sum(\text{Electrical input of technology in each dwelling type}) \times (\% \text{ of total heat pumps into each dwelling type}) = \text{Weighted average electric input of technology type deployed in scenario}$$

Electrical input of LT ASHP in dwelling (kW)		Split of ASHPs between dwelling types		=	4.74 kW
Detached - Low	5.26	Detached - Low	15%		
Detached - High	7.91	Detached - High	11%		
Semi-detached - Low	3.39	Semi-detached - Low	11%		
Semi-detached - High	5.40	Semi-detached - High	14%		
Terraced - Low	2.87	Terraced - Low	22%		
Terraced - High	4.89	Terraced - High	26%		
			100%		

3. $(1) \times (2) \times (\text{Technology load profile normalised for a } 1 \text{ kW appliance}) = \text{Weighted load profile for technology}$



4. $\sum \text{Weighted technology load profiles} = \text{Aggregate heating load profile per dwelling}$



9.3 Major assumptions regarding the network modelling

Key simplifying assumptions include:

- The assumed direct relationship between LV feeder capacity headroom and distribution transformer capacity headroom (as stated above); though of course with increments of standard transformer sizes of around 60% (e.g. 200-315; 315-500; 500-800kVA etc.) it might be that transformer capacity headroom is greater in some cases (especially on tapered LV networks – see considerations and caveats below);
- Utilisation factors for pole-mounted substations (where no data exists) are similar to those of ground mounted substations in the areas concerned;
- That any heat pump or other form of new electrical demand (such as home EV charging) will not worsen any current unbalanced network loading conditions (see considerations and caveats below);
- The assumed degree of correlation (and/or diversity) between new imposed demand due to electrification of heating and the current network demand curve (which in off-gas grid areas will have different characteristics to those serving on-gas grid areas);
- The distribution curve of capacity headroom (i.e. that you derive from such data that is provided) is representative of the population of substations as a whole serving off-gas grid areas.

Some of the more important considerations and caveats include:

- **Transformers tend to come in standard sizes** (e.g. 16, 25, 50, 100, 200, 300/315, 500, 800, 1000kVA), which has an effect on capacity headroom – even at the time of commissioning the substation – and hence on the overall ‘distribution curve’ of capacity headroom is not smooth.
- **LV cables also tend to come in standard sizes** (e.g. imperial sizes: .04, .06, .1, .2, .3 in² / metric: 35, 70, 120, 185, 300 mm²) but ‘tapering’ of LV feeders (common during the latter part of the last century and until relatively recently) means that each section of cable will have been sized according to the anticipated demand on that section (and other factors such as voltage drop, fault level and loop impedance - to ensure sufficient power quality and integrity of protection); hence capacity headroom might be different for each section of any feeder. It follows that individual branches could conceivably become overloaded before the first section out of the substation. There is no way of assessing this other than through modelling of the specific LV networks concerned.
- **Loading across the three phases of a transformer and LV feeders will not be perfectly balanced** – including at times of peak demand – and hence this imbalance will mean that the capacity headroom of the heaviest loaded phase will be less than the others - and since it is largely impracticable to rebalance load on an LV network (albeit it is easier on overhead feeders) the heaviest loaded phase is what will determine the headroom for the substation and feeder as a whole (assuming any new demand is equally spread across the three phases).
- **Voltage could also limit LV feeder headroom.** Whilst thermal ratings are generally the limiting factor, voltage is also an important consideration, and this might be particularly so in the case of rural overhead line feeders (of which there are likely to be a higher proportion in off-gas grid areas). Whilst moderate under (or over) voltage won’t lead to networks being damaged and might not even be noticeable to customers with modern appliances (which tend to be more tolerant of voltage levels) it is nevertheless a legal requirement (note ‘legal’ - not just a licence condition) on DNOs to maintain voltage within defined statutory limits (at LV this is 400/230 +10% / -6%).
- Whilst the analysis is limited to impact on LV networks (since this is where the earliest hot spots will arise) **the upstream impact will also ultimately be significant**. Higher voltage networks are required to have a designed-in level of redundancy* for supply security purposes, and this, rather than thermal capacity headroom per se, is what will trigger reinforcement (or some other form of intervention such as DSR) (*note: the requirement is not actually stated in terms of redundancy but in terms of the demand that must be met within a certain time following a fault outage – but in practice, meeting this requirement requires an element of redundancy - for example N-1 or even N-2 at extra high voltage).
- Whilst the analysis is concerned solely with electric heating, the impact of **EV charging** cannot be ignored as there might be a degree of correlation in the two forms of imposed new network demand (e.g. if EV users choose not to engage with ‘price signalling’ and instead recharge their EVs in the early evening when returning home from work).
- Overall, for networks typically designed on the basis of domestic ADMDs of 1 to 2kW (e.g. for on-gas grid areas) then irrespective of the assessed distribution curve of capacity headroom, it will be apparent that relatively small proportions of consumers adopting electric heat pumps (in addition to any home on-peak EV charging) will result in such headroom rapidly being taken up or exceeded; any feasible measures to ‘shift’ new electric heating demand to avoid current peak demand periods will help, but realistically such options might be limited.
- Domestic properties in off-gas grid areas will tend to have a higher daytime electricity consumption than equivalent properties in on-gas grid areas (some old research I have seen suggests 10 – 15% higher). Consequentially, substations and LV networks serving off-gas grid areas will generally have been designed based on assumed ADMDs for domestic properties higher than those in on-gas grid areas. For example, for newbuild developments in

off-gas grid areas, Eastern Electricity (as was – now UKPN's Eastern Power Networks system) assumed daytime ADMDs for 1/2, 3, 4, >4 bedroom properties of (respectively): 1.5, 1.9, 2.1, 3.1 kW and night-time ADMDs of 2.0, 2.5, 3.0, 3.5kW (note: these figures assume no off-peak electric space heating; where storage heaters and off-peak electric water heating is installed for newbuild properties, then night-time design ADMD was based on actual heating installation capacity multiplied by a factor (typically 0.8 or 0.9) and daytime ADMD was based on total daytime peak heating load multiplied by a smaller factor (typically 0.5 for E7 and 0.7 for pre-E7 restricted hours tariffs).

- This higher loading of networks serving off-gas grid areas also has upstream impacts: for example, in parts of Norfolk some primary (33/11kV) substations have historically had peak demands which occur at night in winter due to storage and water heating load (although the general expansion of the gas grid means that fewer substations now have this night-peaking load profile). This is likely to be true of other networks serving off-gas grid areas, and hence it might be that primary substations and high voltage networks in these areas have a greater capacity to absorb heat pump demand – especially if they have been designed to accommodate high (albeit off-peak) electric heating demand.
- Overall (notwithstanding what your derived capacity headroom distribution curve reveals) networks serving off-gas grid areas should have a greater capacity to serve new heat pump demand than those serving on-gas grid areas – particularly if domestic water heating demand can be restricted to off-peak periods (for example if the properties have large well insulated hot water tanks – quite possibly with immersion heaters).

DNOs are considering (and/or trialling through NIA/NIC projects) a range of 'smart / active network management' solutions that should help release a limited amount of capacity headroom for heat pump demand (albeit their immediate priority is releasing capacity for EV charging) - including DSR/DSM based products, LV 'soft' network meshing, dynamic network reconfiguration, dynamic plant ratings (more relevant to high voltage networks), enhanced voltage control (for voltage and power factor optimisation) and potential phase load balancing technologies. The (now somewhat dated) Smart Grid Forum WS3 report - which led to the Transform model - assumed significant longer-term network investment savings from some of these technologies³³

Power factor

The transformer rating and the maximum demand indicator readings supplied by the DNOs were all in kVA and therefore required the use of a power factor to convert into kW. The power factor used was 0.95. There's little in terms of reactive power data for the lower voltage levels of distribution networks (primarily due to lack of monitoring). However, the nature of domestic load is primarily resistive with relatively little inductive demand; exceptions are induction motors as used in refrigerators – and directly (as opposed to inverter connected) heat pumps - which might tend to reduce overall power factor in future. However, the Distribution and Connection Use of System Agreement (DCUSA)³⁴ requires that users (and generators) constrain their reactive demand (or export) to maintain a minimum power factor of 0.95.

Effect of non-inverter driven heat pumps on the LV network

The reader should be aware of the potential power quality issues that heat pumps could create on 'weak' networks. Some heat pumps have compressors with 'soft-start' features and some are inverter connected; from a power quality perspective these shouldn't cause any significant issues on the LV

³³ EA Technology (2012), *Assessing the Impact of Low Carbon Technologies on Great Britain's Power Distribution Networks*

³⁴ Distribution and Connection Use of System Agreement (DCUSA) 2018, V10.4, <https://www.dcusa.co.uk/SitePages/Documents/DCUSA-Document.aspx> [accessed 21/08/2018]

network (leaving aside any possible harmonics issues related to inverters). However, some heat pump compressors use induction motors with 'direct on-line starting'.

A typical 10kW heat pump will have a 2.5kW compressor motor. Even with a soft-start feature, the starting current will be around twice the normal running current. But for an induction motor with direct on-line starting, the transient starting current can typically be 4 to 7 times the normal running current.

The potential problem this creates is not a 'capacity' issue per se: obviously it's unlikely that heat pumps on any network would all start simultaneously (expect perhaps if they were responding to a tariff price change signal from a smart meter) but even if they did, the duration of any 'overload' they created would be far too short to cause any damage (or a fuse to blow) due to the inherent thermal inertia of the network components.

A 2.5kW compressor would draw around 10 - 11A when running, but on starting it could draw between 42 and 77A. The potential problem this creates is a noticeable voltage dip that all customers connected to the same phase on that feeder (or even that substation) would experience. Heat pumps cycle on and off during operation (except perhaps on exceptionally cold days) and if the network is supplying a high population of properties with heat pumps, then the number and frequency of voltage dips might be unacceptable.

The size of the voltage dip depends on the 'source impedance' (this is the network impedance behind the heat pump connection). The greater the source impedance, the greater will be the voltage dip. For practical purposes on LV networks, the source impedance is a function of the supplying distribution transformer impedance the line (or cable) impedance – both of which are inversely related to the size (rating) of the transformer and line.

An Engineering Recommendation³⁵ – specifies the acceptable limits for the size and duration of voltage dips, and if these limits are exceeded (or anticipated to be exceeded) then the DNO would be obliged to take corrective (or preventive) action (this is effectively a licence obligation) and this could include insisting that all heat pump compressors on the network concerned have a soft-starting feature to limit the starting current.

However, on 'weak' networks - e.g. rural networks served by small pole-mounted transformers (or even branches on underground networks with small cables – such as 35mm² or .04in² – serving several customers with heat pumps) then it could trigger reinforcement: i.e. changing the transformer for one of a higher rating or (less likely) overlaying a small cable. For example, changing a 25kVA pole mounted transformer for a 50kVA transformer would virtually halve the source impedance at the substation LV busbars and hence almost halve the size of any voltage dip (the inductive impedance of a small transformer would be the dominant component of overall source impedance).

Bearing in mind BEIS' recent consultation on 'standards' for smart appliances³⁶, the need for heat pumps to have a soft-start feature could be relevant to that work.

9.4 Load profiles

Table 15 below details the load profiles used in the model.

³⁵ ENA EREC P28: Energy Networks Association – Engineering Recommendation of the Electricity Council

³⁶ <https://www.gov.uk/government/consultations/proposals-regarding-setting-standards-for-smart-appliances>

Table 15: Electricity demand profiles

Data	Source	Notes	Quality score
Base electricity load profiles	Elexon (2018)	Profile classes 1 and 2	high
LT ASHP load profile	Delta-ee	Modelled profiles - ENWL Electrification of heat 2016	moderate
HT ASHP load profile	Delta-ee	Modelled profiles - ENWL Electrification of heat 2016	moderate
LT GSHP load profile	Delta-ee	Modelled profiles - ENWL Electrification of heat 2016	moderate
HT GSHP load profile	Delta-ee	Modelled profiles - ENWL Electrification of heat 2016	moderate
Direct electric load profile	Research article³⁷	Boßmann, Tobias & Staffell, Iain. (2015)	moderate
Storage heaters load profile	Research article³⁸	Boßmann, Tobias & Staffell, Iain. (2015)	moderate

The Network impacts model contains the full details of each profile.

9.5 Temperature scenarios

Two temperature scenarios have been included in the analysis, an ‘average’ peak winter day and a 1-in-20 peak winter day. Figure 22 shows the profile for an ‘average’ peak winter day, when heating systems will typically operate during the morning and evening heating periods to provide space heating. The designed heat pump capacity can meet the heat demand and back up heaters will typically not be required to operate, unless temperatures drop below zero or -1 degrees during the heating periods.

³⁷ Boßmann, Tobias & Staffell, Iain. (2015). The shape of future electricity demand: Exploring load curves in 2050s Germany and Britain. Energy. 90. 10.1016/j.energy.2015.06.082.

³⁸ Ibid.

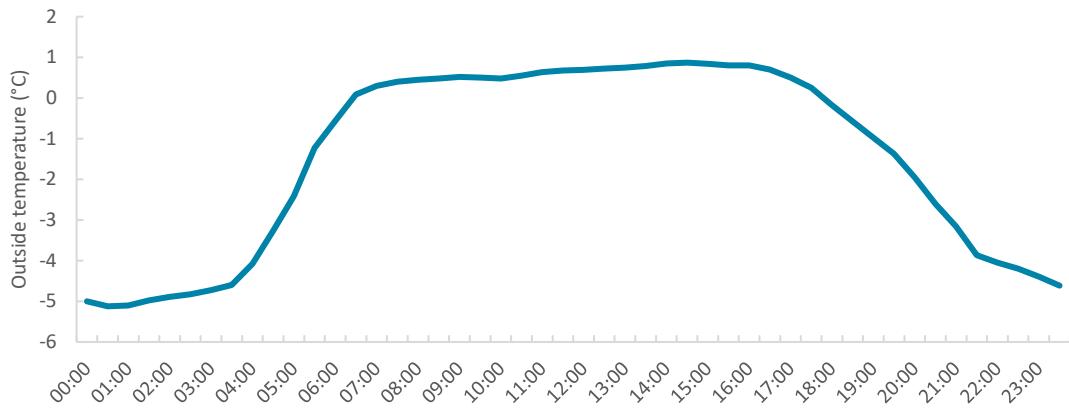


Figure 22: Temperature during an 'average' peak winter day

Figure 23 shows the temperature profile for a 1-in-20 peak winter day where temperatures typically vary from -8 to 0°C. During some of the heating period, the outside air temperature is lower than what the ASHPs have been designed for.

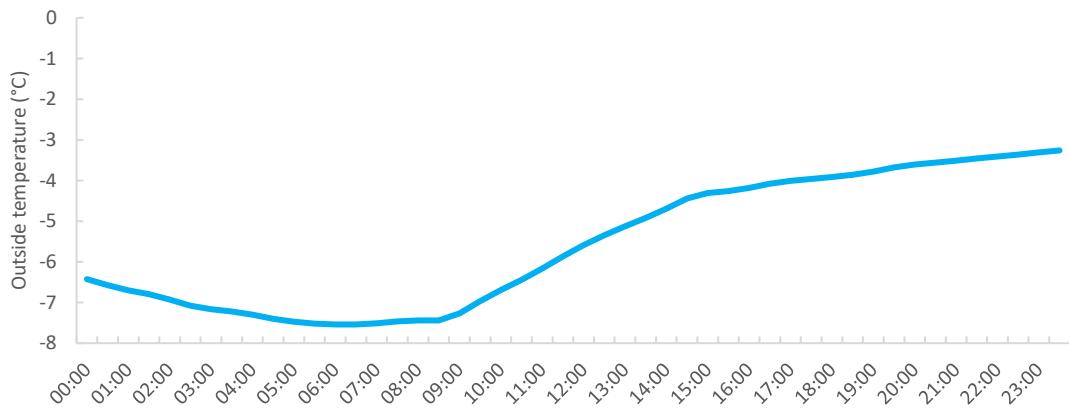


Figure 23: Temperature during a '1-in-20' (extreme) peak winter day

GSHPs have been assumed to be unaffected by outside air temperature.

Disclaimer:

Copyright © 2018 Delta Energy & Environment Ltd. All rights reserved.

Unless otherwise credited all diagrams in this report belong to Delta Energy & Environment Ltd.

Disclaimer

While Delta Energy & Environment Ltd ('Delta-ee') considers that the information and opinions given in this work are sound, all parties must rely upon their own skill and judgement when making use of it. Delta-ee does not make any representation or warranty, expressed or implied, as to the accuracy or completeness of the information contained in the report and assumes no responsibility for the accuracy or completeness of such information. Delta-ee will not assume any liability to anyone for any loss or damage arising out of the provision of this report.

The report contains projections that are based on assumptions that are subject to uncertainties and contingencies. Because of the subjective judgements and inherent uncertainties of projections, and because events frequently do not occur as expected, there can be no assurance that the projections contained herein will be realised and actual events may be different from projected results. Hence the projections supplied are not to be regarded as firm predictions of the future, but rather as illustrations of what might happen. Parties are advised to base their actions on an awareness of the range of such projections, and to note that the range necessarily broadens in the latter years of the projections.