Heat demand mapping and assessment of heat supply options for local areas – the case study of Neath Port Talbot

ABSTRACT

A method for estimating the heat demand of different types of dwellings is described. Furthermore, an optimal heat supply mix for a local area was determined considering gas and electricity prices and the unique characteristics of the local area in terms of the heat demand and potential heat supply options. These methods were demonstrated on the local authority area of Neath Port Talbot in the UK. The estimated heat demand was validated against real data. The modelling results obtained show that significant financial support is required for low carbon heating technologies such as heat pumps and district heating networks for them to play a major role in the decarbonisation of heat.

Keywords: Heat decarbonisation, Heat demand, Local energy system

HIGHLIGHTS OF THE PAPER:

- A method was proposed for estimating heat demand of domestic building.
- A method was used to investigate cost-effective heat supply options for local areas.
- The methods are demonstrated on Neath Port Talbot but can be applied elsewhere.
- District heating and air-source heat pump play major role in decarbonising heat.

NOMENCLATURE

ASHP: Air-Source Heat Pump

BEIS: Department for Business, Energy and Industrial Strategy of the Government of the United Kingdom

CCC: The Committee on Climate Change that is an independent body advising the UK Government on emissions targets.

EPC: Energy Performance Certificate that provides details of the energy performance of a property.

Hybrid HP: Hybrid heat pump which is a combination of a small ASHP with a gas boiler.

LSOA: Lower layer Super Output Areas that give the boundaries of geographical areas which are used to organise national statistics and census data from the Office for National Statistics. A LSOA has on average 1,614 inhabitants and 672 households. There are 34,753 LSOAs in England and Wales [1].

MSOA: Middle layer Super Output Areas that give the boundaries of geographical areas which are used to organise national statistics and census data from the Office for National Statistics. A MSOA is constituted from several LSOAs. There are in average 4.8 LSOAs in each MSOA, for a total of 7,201 MSOAs in England and Wales [1].

SAP: Standard Assessment Procedure developed by the former Department of the Environment of the UK in 1992 to assess the energy performance of dwellings.

1 INTRODUCTION

In 2019, the United Kingdom (UK) amended its previous target of 80% reduction in CO_2 emission by 2050 (compared to 1990 level) to achieve a net-zero economy by 2050. According to the Committee on Climate Change (CCC) [2], this means that 90% of the buildings will be required to have low carbon heating by 2050. As an intermediate target, for producing heat, a carbon intensity of 180 $gCO_{2eq}/kWh_{thermal}$ by 2030 was suggested [3].

In contrast to electrical power supplies, which are being decarbonised rapidly, the heat sector has largely remained unchanged for the past three decades. In 2018, the final energy demand for space heating and domestic hot water of the UK domestic sector was close to 400 $TWh_{thermal}$. This has been stable since 1990 as the decrease in energy consumption by households of 20% has coincided with an increase of the number of households of 20%. The heat demand has been mainly met by consuming natural gas. Since 1990, the share of natural gas in the heat supplied has been above 74% and reached 84% in 2018 [4]. This reflects the low uptake of low carbon heating technologies. The total number of heating systems based on renewable energy approved under the domestic RHI[1] scheme was only 66,317 for the period from April 2014 to January 2019 [5].

The future energy scenarios [6], published by electricity system operator of Great Britain (GB), describes a '*2 degrees scenario'* in which a mix of heat pumps, district heating and hydrogen boilers are responsible for meeting the heat demand in 2050. However, this scenario anticipates decreasing the emissions by only 80% compared to the baseline year of 1990. The Heat Roadmap Europe project for the UK [7] emphasized the use of district heating and the electrification of heat. In a report for the CCC [8], the electrification scenario (high electrification of heat and district heating) and the hybrid scenario (high electrification plus hybrid heat pumps) were the two scenarios with the lowest cost when meeting zero carbon emissions.

The viability of each decarbonisation option not only depends on their costs and performance but also are significantly affected by the local circumstances such as availability of space and level of insulation in buildings, heat demand density in an area [10], the availability of waste heat [11] and existing energy infrastructure (e.g. connection to the gas grid and availability of capacity in the electricity network) [9].

1.1 OBJECTIVES

This study describes methods that were used to look at the challenge of decarbonising the heat sector by considering the national target and what can be done at local level. The contributions of this paper are (a) a method for estimating domestic heat demand at fine spatial resolution for different type of dwellings, and (b) an optimisation model for assessing heat supply options considering different gas and electricity price scenarios as well as local circumstances. These two methods were demonstrated on the local authority of Neath Port Talbot in Wales but can be applied to other areas in the European Union. It is worth mentioning that the scope of this work is limited to residential buildings.

[1] The Renewable Heat Incentives (RHI) is a UK Government scheme to encourage the uptake of low carbon heat technologies.

1.2 Literature survey

The methods to estimate heat demand and the modelling tools for heat planning used in the literature were reviewed and discussed to identify gaps and challenges.

1.2.1 Studies to estimate heat demand

Analysis of local heat supply options requires an estimate of the heat demand from the building stock. This is a challenge due to the limited amount of measured heat demand data available at fine resolution and the lack of consistent building stock information across different areas.

Several methodologies have been used to estimate heat demand in the UK at different spatial scales. At national level, Watson *et al*. [12] combined daily aggregate gas demand for the whole GB and data from a trial project to produce a half-hourly heat demand profiles for GB. This method is suitable for estimating aggregate heat demand at national level due to the large share of gas boilers in GB. However, it is not suitable for estimating heat demand at finer spatial resolution (e.g. by local authority, MSOA and LSOA) due to significant variations in the share of heating technologies.

In [13], the authors used gas consumption data, available at LSOA level [14], to estimate the domestic heat demand. This method provides a good approximation of the heat demand for those LSOAs in which gas boilers are the dominant heating technology.

An alternative approach is presented in [15] that combines building stock information from the Ordnance Survey [16], EPC data and a modelling approach derived from Standard Assessment Procedure (SAP) to estimate heat demand at LSOA level. This methodology requires extensive use of geospatial software and was shown not to be very accurate when compared with published data by BEIS [14].

As part of the Heat Roadmap Europe project, Moller et al. [17] developed a pan European atlas of heat demand with a grid of 100x100m cells. For each cell, the national heat demand for each country was distributed based on quantitative mapping using geospatial methods and extrapolation of the characteristics of the Danish building stock. This approach has the advantage of providing heat demand at fine spatial resolution and being replicable in other countries. However, it does not offer a detailed representation of the building stock which could impact the outcomes of the model and it is difficult to overlay the findings of this study on the UK geographic areas (i.e. LSOAs).

1.2.2 Models to study the decarbonisation of heat

The challenge of decarbonising heat has led to a growing number of research studies on the heating sector. Several approaches have been developed and the heat supply options were shown to be impacted by modelling assumptions including spatial resolution and details of the building stock.

The impact of spatial resolution on the outcomes of a model optimising heat supply options in urban areas was demonstrated in [13]. The uptake of district heating networks was assessed using data at three levels of spatial resolution: LSOAs, MSOAs and local authorities in the UK. The results of the model showed a 20% increase in the number of dwellings connected to district heating networks when using LSOA compared to MSOA as the spatial resolution. Using LSOA instead of Local Authority area, as the spatial resolution, resulted in a 30% increase in the number of dwellings connected to heat networks.

Dodds et al. showed in[18] that the use of a more detailed building stock model would have a direct impact on the heat supply options. The outcomes of two versions of the MARKAL model were compared: the base version and a revised version which included a simplified housing stock model. The disaggregated results from the revised version show the impact of the house type on the selected heat technologies whilst providing similar aggregated heat demand with the base version of the model.

There are a limited number of studies that investigated heat decarbonisation in local areas considering fine spatial resolution with detailed representation of the building stock. Scamman et al. in [19] reviewed models recently used to assess the UK heat decarbonisation strategy and only the model used in [13] was found to be suitable. Outside the UK, additional models were identified in the literature which optimise heat supply options by individual buildings, sectors or areas.

The heat supply options for 69 buildings near Porto, Portugal were assessed [20]. For each building, the heat demand and the temporal profiles were estimated and simulated in five scenarios. The results suggested that district heating using waste heat and individual heat pumps with photovoltaics panels were the cost-competitive options.

The authors of [21] investigated scenarios including different levels of expansion of the existing district heating network, individual heating systems and heat savings for Helsingør in Denmark. They divided the local authority into smaller areas based on the heat density and the proximity to the existing district heating. Simulating eight scenarios and using a least-cost approach, they suggested that an expansion of 39% of the district heating and 39% heat savings could be reached.

Additional studies focusing solely on district heating used similar approaches. Several heat decarbonisation scenarios for an existing district heating in a German city were analysed by [22]. An energy dispatch model with the heat demand represented by a single node was used and results suggested that large scale heat pumps integrated into district heating help with the heat decarbonisation, but their viability depends on electricity and CO2 prices. Using a heat demand atlas [17], a custom-build model was built to assess the areas viable for district heating by aggregating the results from each 100x100m cells [23]. The results show that 59% of the 2015 heat demand from the countries considered is economically viable to be supplied by district heating.

2 METHODS

Figure 1 shows the flow chart that describes the methods developed in this study and how they interact with each other. It entails 3 main steps:

1. **Estimating the domestic heat demand** of a local area, using a bottom-up approach, by combining building stock data with the energy performance information of each dwelling.
2. Constructing a **district heating system model** using inputs of local area data, techno-economic data and estimated heat demand.
3. Constructing an **individual heating systems optimisation model** using inputs of local area data, techno-economic data and estimated heat demand.

To assess the heat supply options, the annualised costs of the district heating system and individual heating systems were compared and the option with the lowest annualised cost was selected as the cost-effective way to decarbonise the heat supply in a selected area. Indicators such as CO2 emissions, heat supply mix and levelized cost of heat were calculated.

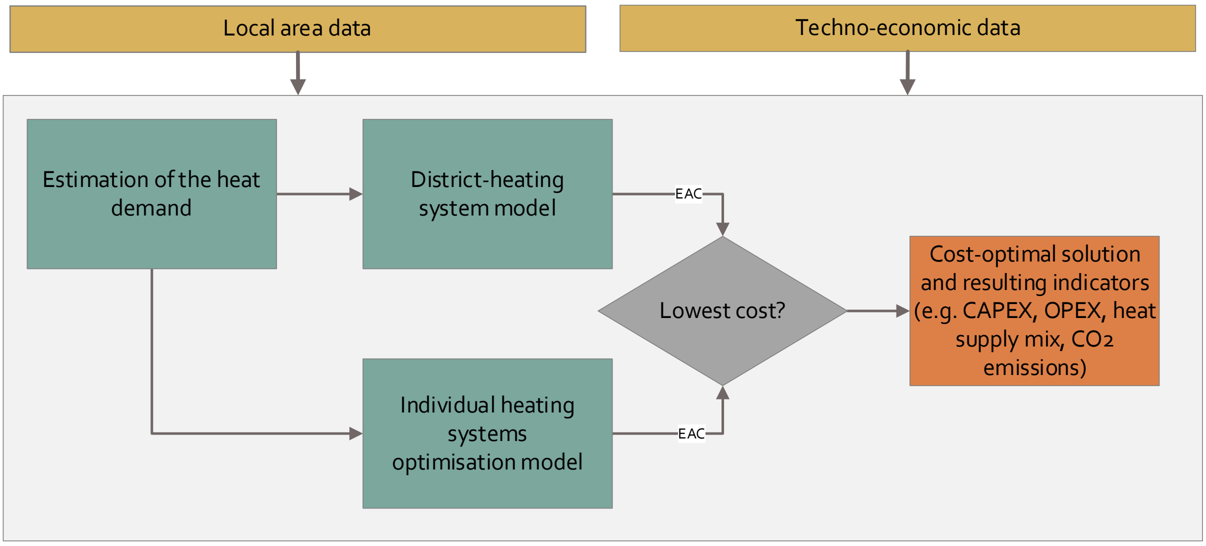

Figure 1: Overview of the methodology of the study

2.1 Estimation of domestic heat demand

Energy Performance Certificates (EPC) were used to estimate the annual heat demand of different dwelling archetypes within a local area. The total heat demand for the local area was derived by multiplying the average heat demand of each dwelling archetype by the number of dwelling archetypes.

Figure 2 illustrates the methodology that was used to calculate the domestic heat demand of a local area. For a local area,

1. The EPCs of dwellings were collected,
2. The identified EPCs were grouped by dwelling archetypes,
3. The heat demand was estimated for each dwelling archetype from the EPC space heating costs and the fuel costs,
4. As not all the dwellings have an EPC in a local area, when the number of EPCs for a dwelling archetype was too low to estimate the average heat demand, the average heat demand for this dwelling archetype was calculated by running steps 1 to 4 for an extended area.

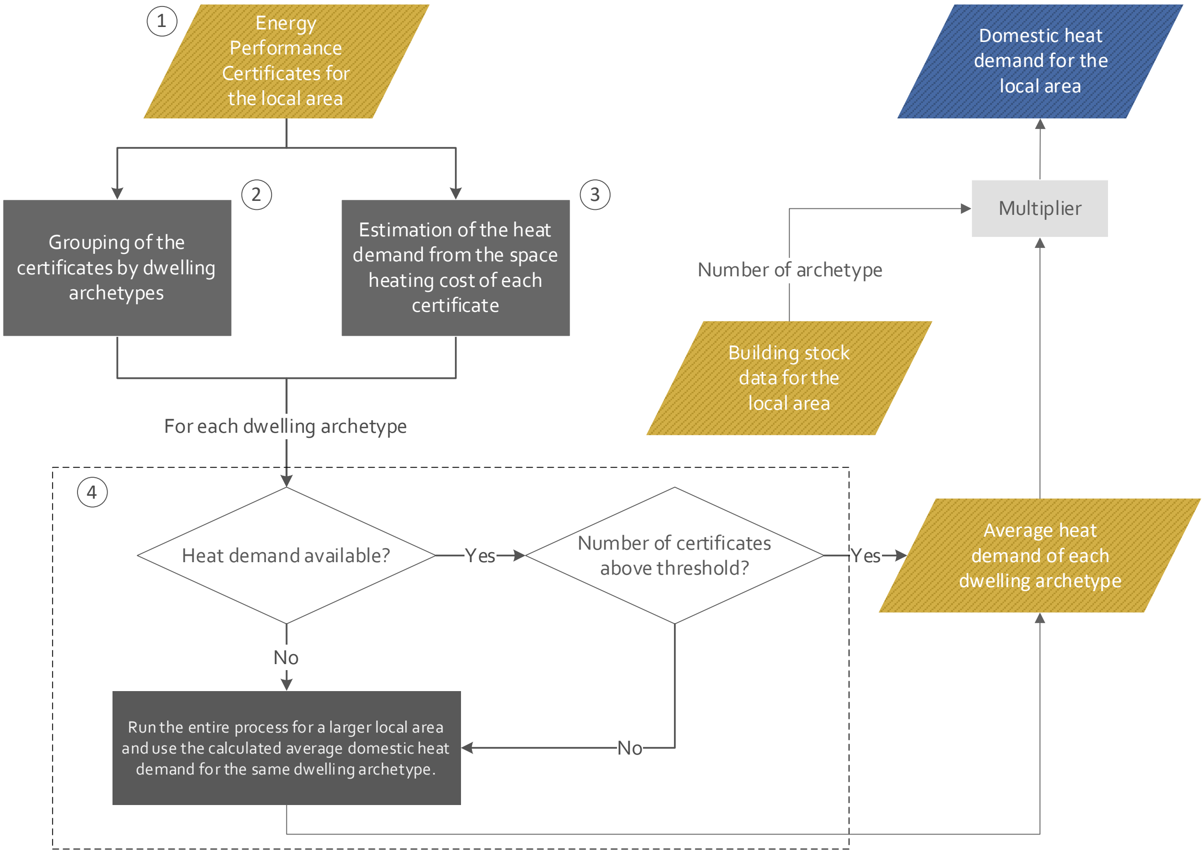

Figure 2: Diagram of the process used to estimate the heat demand of a local area

2.2 The district heating system model

The cost related to a district heating scheme is the cost for the heat supply S and the cost for the heat distribution D. The annual expenditure was calculated using equation 1.

$$Annual\ expenditure = (S_{CAPEX} + D_{CAPEX}) \times \frac{DR}{1-(1+DR)^{-n}} + S_{OPEX} + D_{OPEX} \qquad (1)$$

With DR the discount rate (4%) and n the lifespan of the district heating system (40 years).

2.2.1 The heat supply costs of district heating systems

The technologies considered to supply heat to a district heating system included gas boilers, gas CHP units and large-scale heat-pumps. The installed capacities for these technologies were calculated by identifying the combination which minimised the annual heat supply cost. The methodology used is from [24]. It combines the use of screening curves with load duration curve. The screening curves compares technologies in terms of cost and full load hours. This information transposed on to the load duration curve was used to calculate the capacity installed and the heat demand supplied. This information was used to calculate the CAPEX and OPEX of the heat supply.

2.2.2 The heat distribution network costs

The cost of the district heating network in each local area was determined by the length of the pipes, their diameter and the type of area (e.g. rural, urban).

Equation 2 was used to calculate the average pipe diameter of a district heating scheme for a local area. With $Q_{local\ area}$ $[GJ]$ the heat sold in the local area , L $[m]$ the length of network and $Q_{local\ area}/L$ the linear heat density. Equation 2 were derived by [25] through fitting a logarithmic function to estimate the relationship between average pipe diameter $d_a[m]$ and linear heat density $[GJ/m]$ of 134 district heating schemes in Sweden.

$$d_a = 0.0486 \times ln(Q_{local\ area}/L) + 0.0007 \quad (2)$$

In this paper, the heat sold is assumed to be equivalent to the heat demand and the length of the local road network is used as a proxy for the length of the pipes.

Then according to [24], the heat distribution network cost D_{CAPEX} is a function of the average pipe diameter, the length of the network and the area characteristics as defined by equation 3.

$$D_{CAPEX} = (C_1 + C_2 \times d_a) \times L \quad (3)$$

Where C_1 and C_2 are the construction costs of heat networks for the local area shown in Table 1. These costs were adapted from [25] which estimated them from district heating systems built in Sweden. The original costs were converted from Euros to British pounds using 0.88 €/£ exchange rate, and the area characteristics renamed to fit the UK classification for the level of the urbanisation of local areas.

Local area characteristics	**C1 [£/m]**	**C2 [£/m²]**
Urban > 10k	252	1,779
Village, town and fringe	188	1,518
Hamlet & isolated dwellings	133	1,213

Table 1: Construction cost by local area characteristics.

As shown by equation 4, the variable cost of 0.361 £/GJ was assumed for heat supplied by district heating networks [26]. The variable cost accounts for electricity consumption of pumps and heat losses (heat losses estimated at 8% of the supplied heat). This is a simplification which considers that regardless of the system characteristics the consumption of electricity for pumping water in the network is proportional to the heat supplied.

$$D_{OPEX} = Q_{local\ area} \times (1 + 0.008) \times 0.361 \quad (4)$$

The cost of the substation that links the district heating network to the building heating system was also considered. The major driver for these connection costs is the dwelling type. For a flat, the costs are shared by the other flats of the building, thus it does not cost as much as for connecting a house. In this paper, the average figures from [27] were used for the connection costs: £7218 or £649 equivalent annual cost for houses and £4621 or £416 equivalent annual cost for flats.

2.3 THE INDIVIDUAL HEATING SYSTEMS MODEL

As an alternative to district heating, possible heating systems for individual dwellings were assessed using an optimisation model. The objective of the model was to find the cost-optimal individual heating technology for each dwelling archetype in a local area.

The annual expenditure of the cost-optimal individual heating systems for a local area was calculated as the sum of the equivalent annual CAPEX (I_{CAPEX}), the annual OPEX (I_{OPEX}) and the annual cost of reinforcements of the power sector (I_{RC}) shown by equation 5.

$$Annual\ expenditure = I_{CAPEX} + I_{OPEX} + I_{RC} \quad (5)$$

The problem was formulated as a mixed integer linear programming where the objective was to minimise the annual expenditure of the system as shown by equation 7. It was implemented in Python using the Pyomo optimisation modelling language [28], [29] and the IBM CPLEX solver.

$$Obj\text{: min } Z = (I_{CAPEX} + I_{OPEX} + I_{RC}) \tag{6}$$

$$I_{CAPEX} = \sum_f \sum_d [EAC_{f,d} \times N_{f,d}] \tag{7}$$

$$I_{OPEX} = \sum_f \sum_d \left[\frac{Q_d}{\eta_f} \times O_{f,d} \times N_{f,d}\right] \tag{8}$$

$$I_{RC} = \sum_f \sum_d [ADMD_{f,d} \times RC \times N_{f,d}] \tag{9}$$

Z is the cost function.

$d \in dwelling\_\text{arche}type$.

$f \in future\_tech$, the list of technologies by which current heating technologies can be replaced. It includes gas boilers, resistance heaters, biomass boilers, ASHP, GSHP with borehole and hybrid heat-pumps.

$EAC_{f,d}$ is the equivalent annual cost of technology f in the dwelling archetype d that includes cost of capital and the fixed annual operation and maintenance cost. Q_d is the annual heat demand of the dwelling archetype d. η_f is the efficiency of the technology f. O_f is the variable operation cost (£/kWh) of technology f which includes the fuel costs and CO_2 costs minus any incentives. $N_{f,d}$ is the number of dwellings corresponding to archetype d where the future technology f is installed. $ADMD_{f,d}$ (kW) is the after diversity maximum electricity demand of the technology f installed in the dwelling archetype d. RC the network reinforcement cost (£/kW) to cover the potential increase of the peak of electricity demand.

The constraints of the model include that gas-based technologies cannot be installed in a dwelling not connected to the gas grid. It was implemented by setting to 0 the number of dwellings not connected to the gas grid and being converted to a heating technology using natural gas.

The number of dwellings with biomass boilers in urban areas cannot increase. The number of dwelling archetypes where the heating technology was biomass boiler in the input data were set to be below or equal to the number in the output of the model.

Other constraints were enforced through cost and choice of the list of future technologies. When a technology was unlikely to be installed in a specific type of dwelling the cost of this unit was set high (see appendix). Future technologies did not include oil boilers.

3 RESULTS

The methods described in this paper were demonstrated on the local authority of Neath Port Talbot (NPT) in Wales. NPT has a mix of rural and urban areas that are not all connected to the gas grid. NPT was divided into 91 local areas (LSOAs) using the UK geographic system for statistics. For each of these LSOAs, the number of dwellings, their types and their heating system were extracted from the publicly available statistics [1].

Figure 3 shows the number of heating installations by dwelling type currently used in NPT [1]. The gas boiler is the dominant heating technology. Semi-detached and terraced dwellings are the main dwelling types. There is a total of 57,891 dwellings in NPT. This data was used to define 16 dwelling archetypes, with an archetype being the combination of a dwelling type and a heating system.

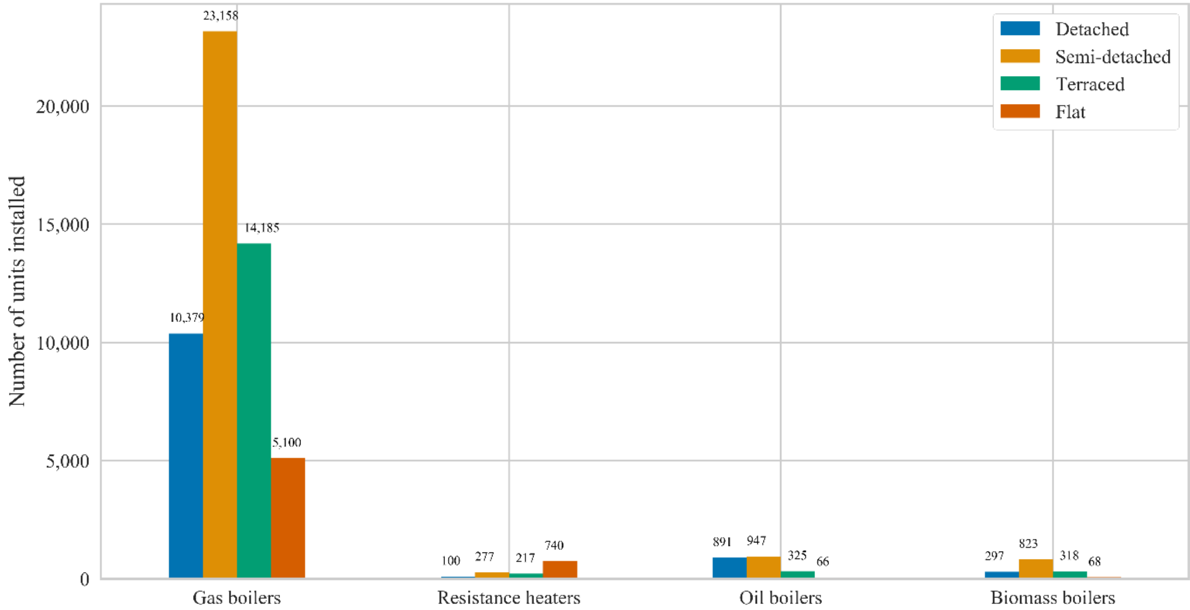

Figure 3: Heating currently installed in dwelling types in Neath Port Talbot

Figure 4 shows the current share of gas, oil and biomass boilers based on the total number of dwellings in each LSOA. The LSOAs with low share of gas boilers are the LSOAs with the fewer dwellings connected to the gas grid. Oil and biomass boilers usually are used where there is no gas connection.

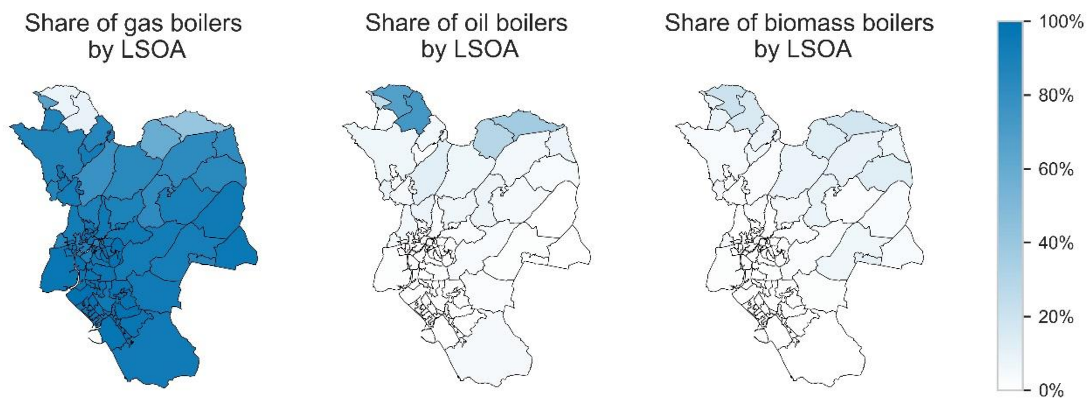

Figure 4: Maps of Neath Port Talbot showing the current share of heating technologies

3.1 Heat demand of dwellings in Neath Port Talbot

The EPC certificates for NPT [30] were collected and mapped to the 91 LSOAs and the heat demand by LSOA was calculated as described in section 2.1. Figure 5 shows the estimated average annual heat demand by dwelling archetype in NPT. Detached dwellings have the highest heat demand on average, followed by semi-detached, terraced and flats. For a given dwelling type, the annual heat demand varies depending on the heating fuel used. This is explained by the differences in the characteristics of these dwelling archetypes: age of the dwelling, gross internal area, and energy efficiency level. For instance, detached dwellings with resistance heaters are on average smaller in size and more energy efficient than detached dwellings with oil boilers.

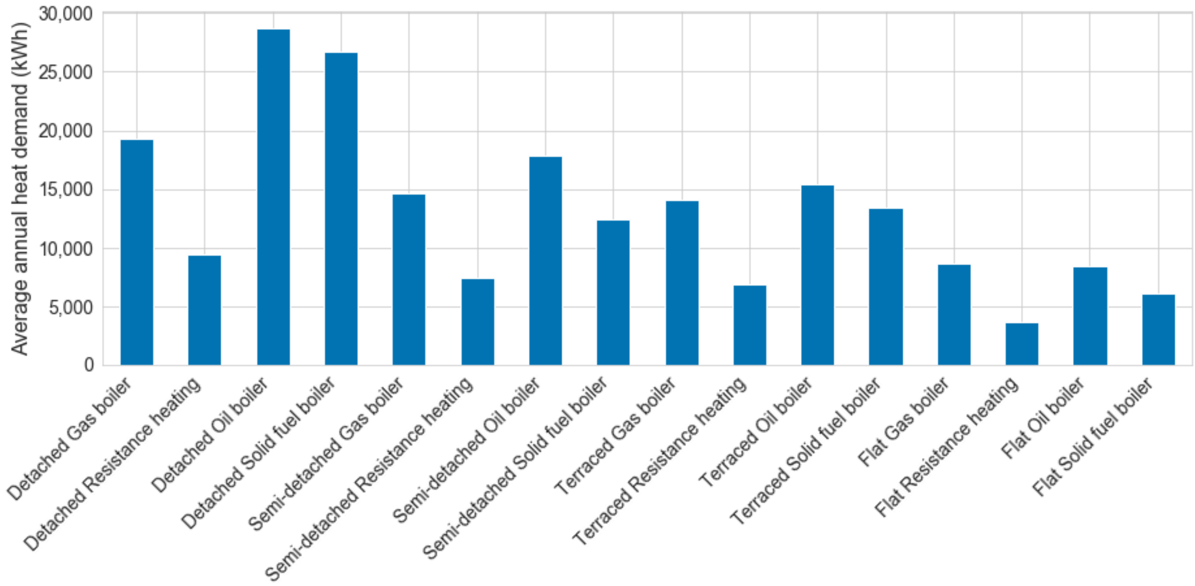

Figure 5: Average annual heat demand by dwelling archetypes in Neath Port Talbot

The Centre for Sustainable Energy (CSE) published a study, based on 32,700 surveys done in Great Britain, about the energy usage of different dwellings which included average annual heat demand by heating fuels: gas, electricity and non-metered fuels (e.g. oil and biomass) [31]. Figure 6 shows the comparison of the heat demand from the CSE study with the aggregated estimated heat demand by heating fuels of the dwelling archetypes shown in Figure 5.

For the three type of dwellings, the values are in the same range. The largest discrepancy was observed for the non-metered heated dwellings, where the annual heat demand from the CSE study is 20% lower than the estimated heat demand in NPT. Two main reasons might explain these differences: the accuracy of the heat costs estimated in the EPCs and the efficiency rating of the technologies assumed.

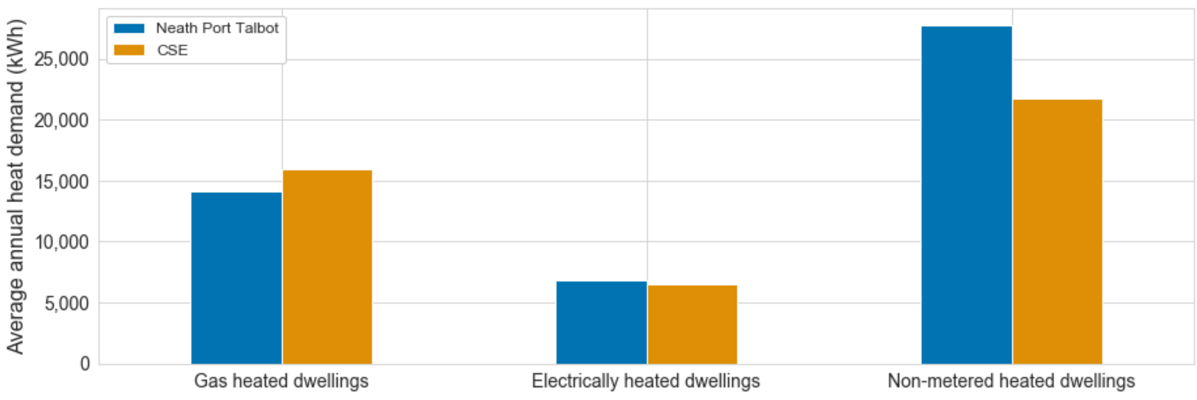

Figure 6: Average annual heat demand for gas, electrically and non-metered heated dwellings in the CSE report [31] and in Neath Port Talbot.

The total heat demand for each LSOA was derived by multiplying the heat demand of each archetype by the number of dwelling archetype known from the 2011 census data [1]. Figure 7 shows that the estimated heat demand in NPT for each LSOA range from 6,390 MWh to 16,850 MWh.

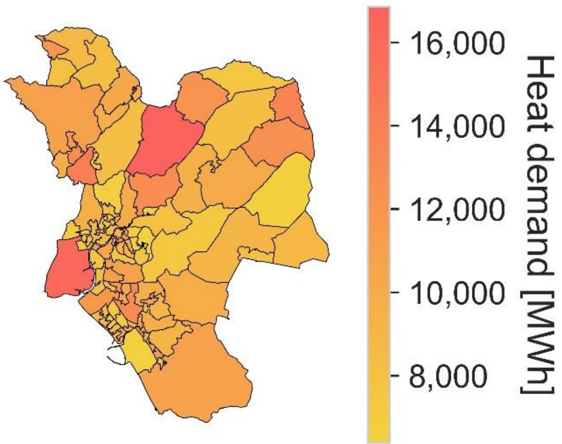

Figure 7: Map of Neath Port Talbot showing the estimated heat demand for each LSOA

3.2 Assessment of heat supply options in Neath Port Talbot

Using the methodology shown in Figure 1, cost-optimal heat supply technologies were determined for each of the 91 LSOAs in NPT for different combinations of electricity and gas prices. The input data for the modelling, which include the techno-economic data of the heating technologies is available in the appendix. The resulting heating technologies, carbon intensity and levelized cost of heat at local authority level are presented followed by the spatial results for two combinations of electricity and gas prices.

3.2.1 Scenario definition

Figure 8 shows the 90 possibilities of gas and electricity prices with each dot representing a scenario. These are referred to as '*price scenarios*' hereafter.

The changes in biomass and oil prices were assumed to be proportional to the changes in the gas price. The remaining assumptions and input parameters to the models are listed in the appendix.

As a point of reference, the prices for 2018 were: 17.9 p/kWh for electricity [32], 4.4 p/kWh for natural gas [32], 5 p/kWh for biomass [33] and 5 p/kWh for oil [32]. The closest *price scenario* to the 2018 prices is the scenario where the electricity price is 17 p/kWh and the gas price is 4 p/kWh. This is referred to as '*2018 price scenario*' and is shown as a red cross in Figures 8 to 11.

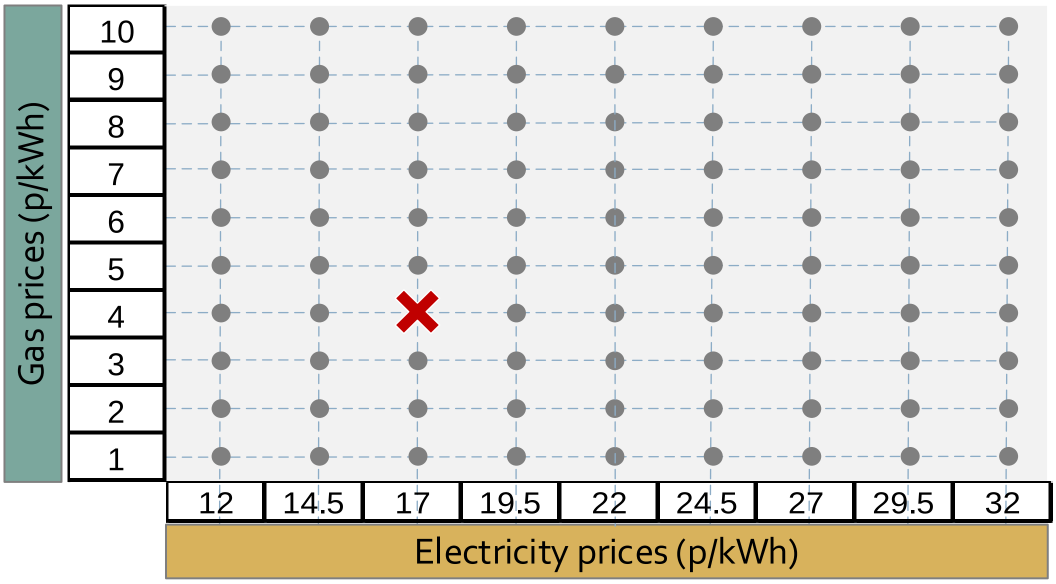

Figure 8: Combinations of electricity and gas prices modelled to create price scenarios.

The results for NPT were then produced by aggregating the results of the NPT LSOAs for each price scenario.

3.2.2 The heating technologies

Figure 9 shows the two technologies with the largest shares of heat supplied for each price scenario. The two prevalent heating technologies are referred to as the main and secondary technologies. Low gas prices favours gas-based technologies whereas high gas prices favours electricity-based technologies. For the *2018 price scenario*, the main technology chosen is gas boiler and the secondary technology biomass boiler, which shows the model output is similar to the real situation in 2018.

When the gas price increases, electricity-based technologies become more attractive. This is shown by the red (6), purple (7) and blue (3) areas, where individual ASHPs and district heating using large scale heat pumps are chosen as either main or secondary technologies. In contrast, when the electricity price increases, the pink (9), brown (8) and green (5) areas that show gas-based technologies become attractive.

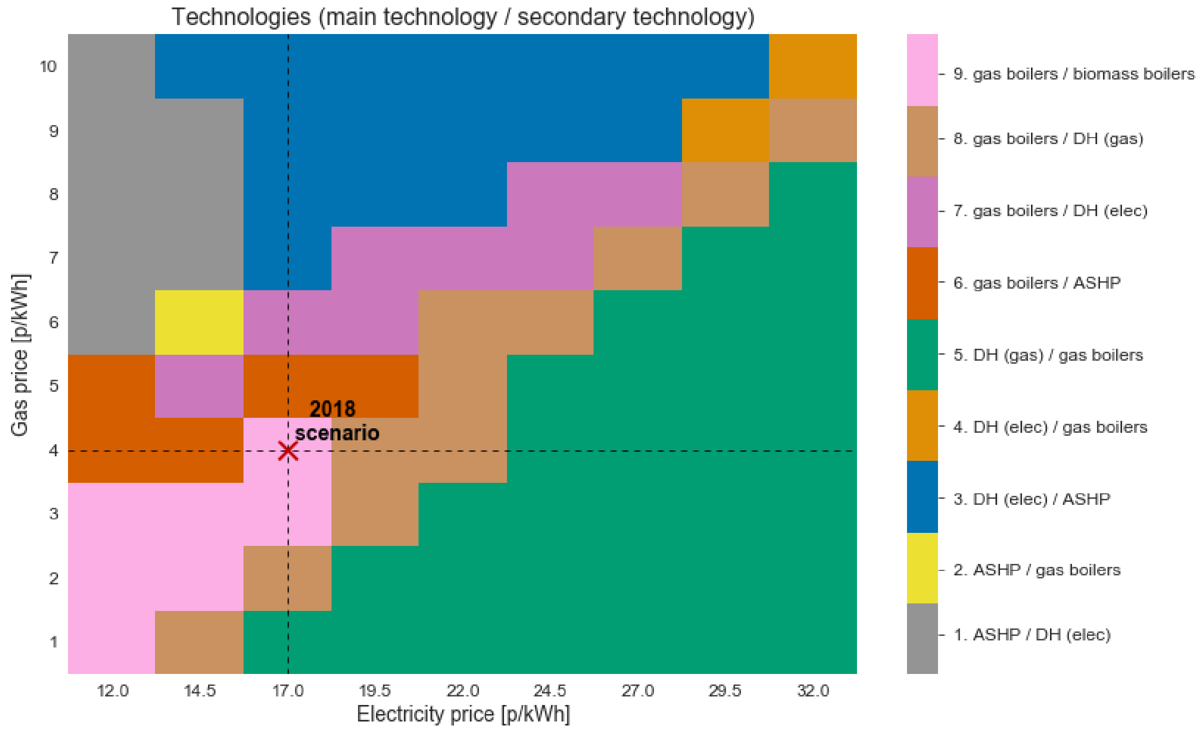

Figure 9: Colour map displaying the main and secondary technologies for each price scenario (each rectangle represents one price scenario). DH stands for District Heating. (colour to be used in print)

3.2.3 The carbon intensity of heat

Figure 10 has two areas, showing where the carbon intensity of the price scenarios is below and above the intermediate target of 180 gCO2/kWh suggested by the CCC. Only price scenarios with an electricity to gas price ratio below 2.4 or gas prices over 5 p/kWh meet this target. The scatter points correspond to historical prices (+), 2018 prices (x) and projected prices (Δ) from BEIS [4]. BEIS used these prices in an econometric model to project the UK energy demand and greenhouse gas emissions and assess the progress towards the UK emissions targets. It was observed that all the price scenarios close to past, present and projected prices have a carbon intensity above 180 gCO2/kWh.

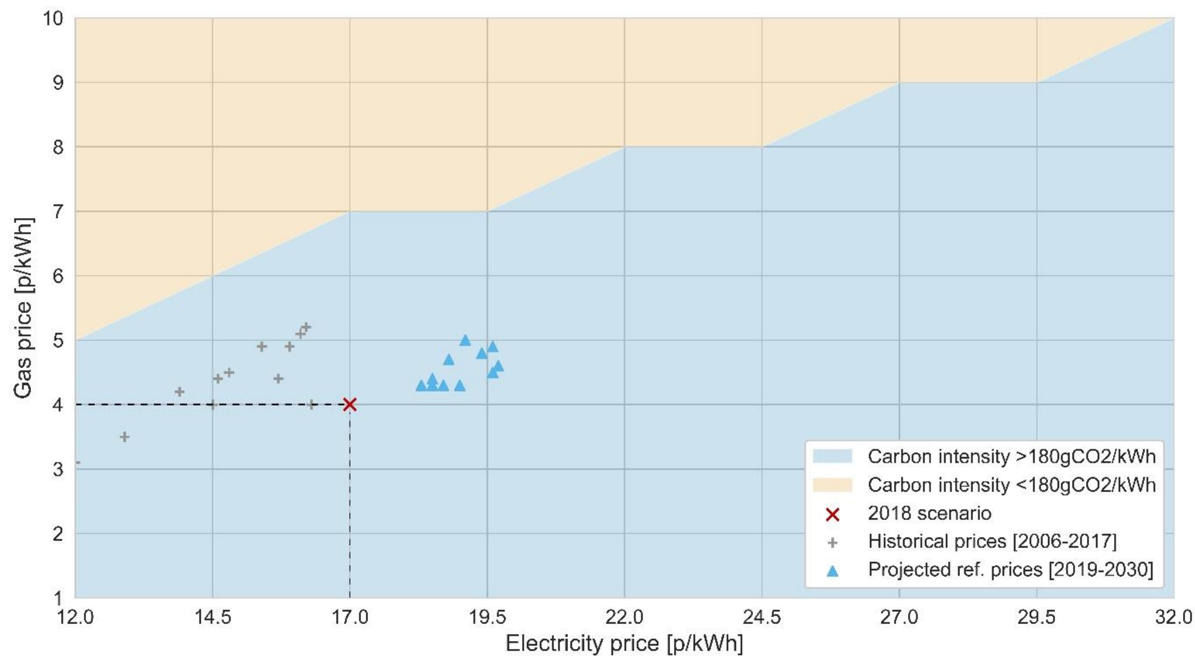

Figure 10: Carbon intensity of the price scenarios. The carbon intensity values were interpolated for those energy prices that were not modelled. (colour to be used in print)

3.2.4 The levelized cost of heat

The levelized cost of heat (LCOH) was used to assess and compare technologies with different characteristics such as lifetime, CAPEX and OPEX. Equation 10 was used to calculate the LCOH for NPT.

$$LCOH_{NPT} = \frac{CAPEX_{NPT} + OPEX_{NPT}}{Heat\ demand_{NPT}} \tag{10}$$

For the *2018 price scenario*, the LCOH was 6.9 p/kWh$_{thermal}$. This value was used as a point of reference to calculate the relative percentage change of the LCOH for different price scenarios; as shown by Equation 11.

$$LCOH\ change\ (\%) = \frac{LCOH_{scenario}}{LCOH_{2018}} - 1 \tag{11}$$

Figure 11 shows four levels of LCOH change of the price scenarios using contour lines. They are displayed overlaying the carbon intensity areas shown in Figure 10. The price scenarios that are close to the 0% line (i.e. negligible changes in LCOH compared to the *2018 price scenario*) have a gas price between 0.04 and 6 p/kWh. When the gas prices are higher than that, the LCOH change gets closer to +25% and can rise to more than +50%.

The price scenarios that meet the carbon intensity target shows a LCOH change less than +25% if the electricity price is below 15 p/kWh and the gas prices is above 5 p/kWh. If the electricity price is the same than in the 2018 price scenario (17 p/kWh), the gas prices is above 7 p/kWh and the LCOH change is above +25%.

The price scenarios annotated as points 1 and 2 are two scenarios close to the 2018 price scenario which are studied in the next section.

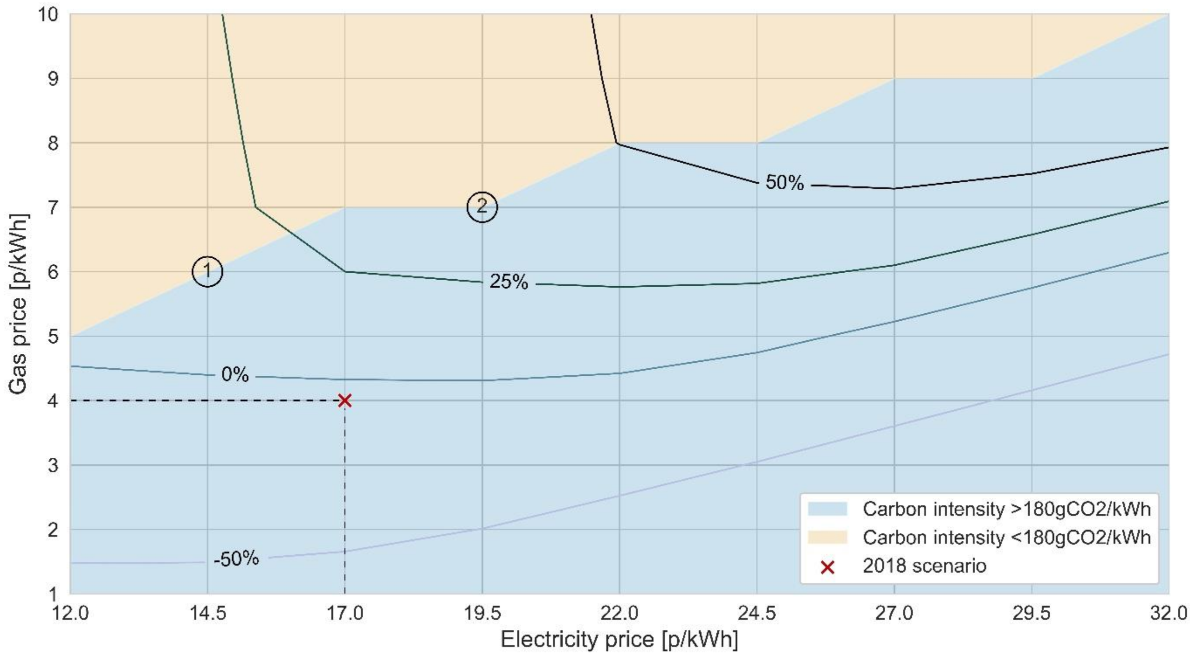

Figure 11: Contour lines showing the percentage change of the LCOH of the price scenarios compared to the 2018 scenario. (colour to be used in print)

3.2.5 Spatial comparison of two price scenarios

Table 2 lists the characteristics of the price scenarios 1 and 2 which meet the intermediate carbon intensity target.

	Electricity price (p/kWh)	Gas price (p/kWh)	Percentage change of the LCOH	Carbon intensity (gCO2/kWh)
Scenario 1	14.5	6	20%	131
Scenario 2	19.5	7	39%	140

Table 2: Characteristics of the two price scenarios selected

In the price scenario that is shown as point 1, the main fuel for heating is electricity (see Figure 9) with 28% of heat supplied by ASHPs and 29% by large heat-pumps in district heating. The remaining heat demand is supplied by gas boilers (40%) and biomass boilers (3%).

In the price scenario 2 shown as point 2, 15% of heat is supplied by ASHPS and 37% by large heat-pumps in district heating. The remaining heat demand is supplied by gas boilers (45%) and biomass boilers (3%). The increase in district heating share is explained by the higher energy prices making this technology more viable than in the price scenario 1.

Figure 12 shows the share of heating technologies by LSOA for the two price scenarios. The adoption of the technologies is different in each LSOA. The LSOAs with higher linear heat density are converted to district heating. ASHPs and gas boilers supply the heat in the other LSOAs.

The share of ASHPs and gas boilers varies from one LSOA to another due to the type of buildings and heat demand. In the price scenario 1, 16 LSOAs have a share of ASHPs above 80% which leads to LSOAs not requiring a gas grid for heating anymore. This is not as significant in the price scenario 2 where gas boilers remain dominant outside of the LSOAs converted to district heating. This reflects that the heat decarbonisation is not happening at the same rate in every LSOAs.

The increase of gas and electricity prices from the price scenario 1 to the price scenario 2 does not change the core set of LSOAs viable for district heating. The LSOAs viable for district heating in scenario 1 are also viable for district heating in scenario 2. Hence, converting these LSOAs to district heating could be considered as a low regret path when looking at energy planning strategies.

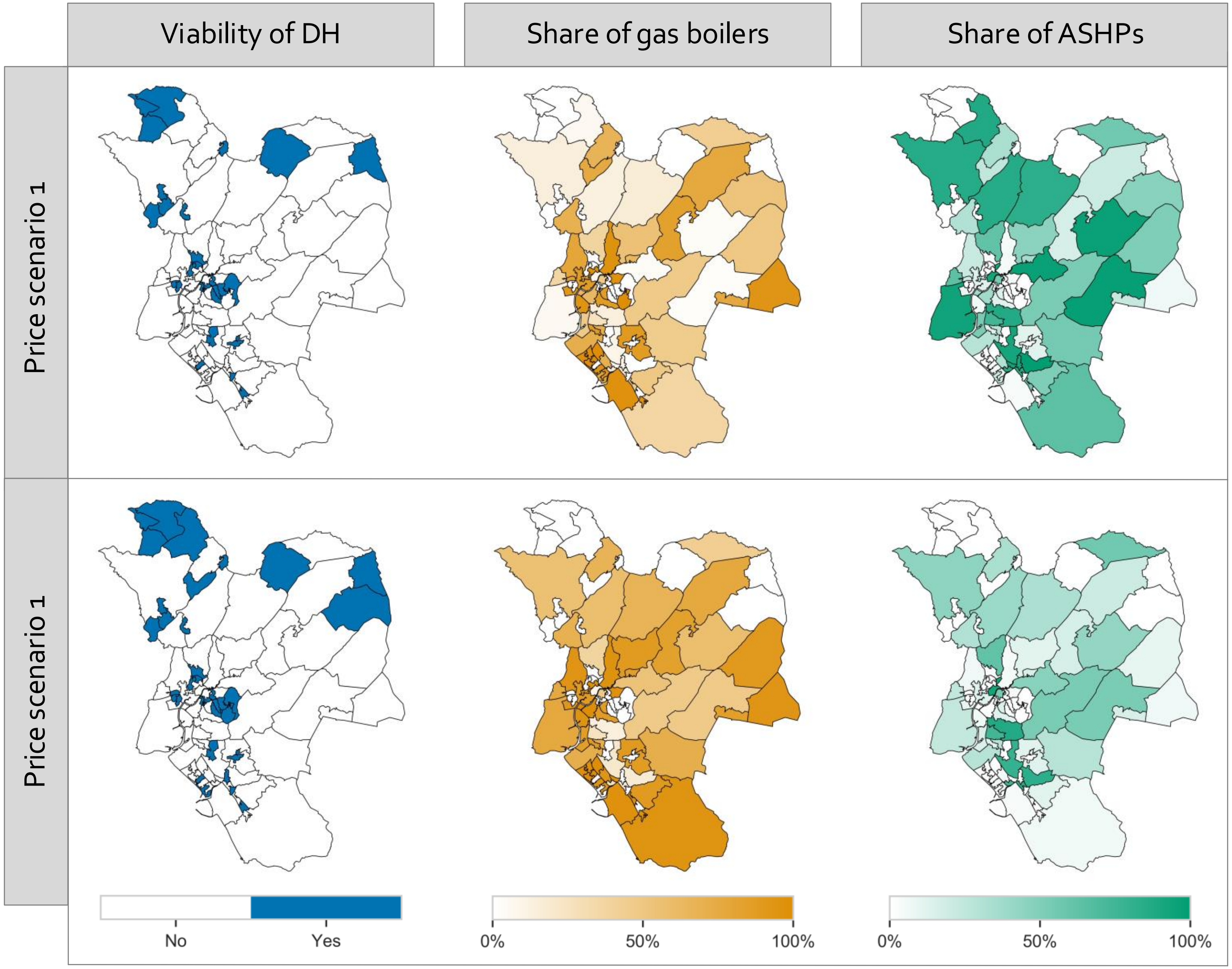

Figure 12: Heating technology uptake at LSOA level for the price scenario 1 and 2.

4 DISCUSSION OF LIMITATIONS OF THE STUDY

A number of limitations occur in this study. The improvement of the energy efficiency of the building stock can decrease the heat demand and impact the choice of the heat supply options. Below a given annual heat demand, technologies with high capital costs lose their competitive advantage against other technologies as the amount of heat supplied or their operating time is too low. In this study, the increase in energy prices are not combined with a decrease of the heat demand and this could impact the choice of heat supply options. For district heating, a decrease of the heat demand would mean a decrease of the linear heat density and impact its viability. For individual technologies, further investigation is required to identify the link between heat demand, installed capacity and annual expenditure.

The cost of district heating is based on cost data from case studies in Sweden. However, the district heating market is very different in UK and Sweden. The current share of district heating in the UK is around 2% compared to 50% in Sweden. This gap could be explained by the lack of incentives, knowledge of the public, engineering skills and regulations which have been identified as barriers to the development of district heating in the UK [34]. With higher district heating cost, the viability of the district heating in some LSOAs could be impacted.

Regarding the method to estimate heat demand, replicability will be determined by the availability of Energy Performance Certificates. Public registers of EPC are not available in all EU regions and thus alternatives method would need to be used to estimate heat demand for different dwellings at local areas. Furthermore, EPC have limitation due to the methods used to produce them and the quality of the recording [35] which may impact the results.

The size of the local area does not stop from running the models, but the choice of the heat supply options as shown in the literature survey. Hence, to replicate the results, a LSOA resolution or a local equivalent need to be used. The heat supply technologies for district heating or the set of individual technologies can be adapted to fit the local constraints.

5 CONCLUSIONS

The methods developed in this paper were demonstrated on the local authority of Neath Port Talbot but can be applied in any other local areas in which relevant data are available.

It was shown that EPCs can be used to estimate domestic heat demand for different dwelling archetypes and aggregated results of heat demand estimates were aligned with figures from another source. This method gives the opportunity to conduct analysis for heat decarbonisation by looking at smaller areas whilst keeping a good representation of the building stock.

The capabilities of the models for investigating optimal heat supply options at local area level were presented. From a high-level point of view, it was observed that in NPT:

- The current mix of heat supply based on gas boilers cannot meet the intermediate target of 180 $gCO2/kWh_{thermal}$ suggested by the CCC.
- The gas price needs to be higher than 5 p/kWh to start driving the replacement of gas boilers and thus, the decarbonisation of heat.
- District heating with large heat pump and ASHP in buildings are two key technologies identified for the decarbonisation of heat.

- Hybrid heat-pumps and ground source heat pumps are not chosen by the model because of their higher costs compared to other technologies.
- The changes in technology and energy prices required to decarbonise heat will conduct to an increase of the levelized cost of heat, which could be above 25%.

It was shown that the share of gas boilers could significantly decrease in some LSOAs. This could affect the economic viability of maintaining a low-pressure gas network and require reinforcement of the electricity network depending on the technology replacing them.

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The data analysis was performed using Python 3.x and the libraries Pandas, Matplotlib, Seaborn and Geopandas.

APPENDIX

A. HEAT LOAD DURATION CURVE IN A LOCAL AREA IN THE UK

A heat load duration curve was built for each LSOA by using the heat demand profile from gas boilers and the estimated domestic heat demand. Currently, gas boilers are the main source of heat in NPT thus having the half-hourly consumption profile of a pool of gas boilers gives a good estimate of the heat demand profile. The Energy Demand Research Project [36] published gas consumption at half-hourly resolution for 14,000 households from early 2008 to the end of 2010. The hourly heat load duration curve was derived from this data by aggregating and averaging the heat demand for each timestep of a dataset containing data for the 14,000 households. It was then scaled based on the estimated domestic heat demand of the LSOA.

B. ASSUMPTIONS REGARDING THE CONNECTION TO THE GAS NETWORK OF THE DIFFERENT BUILDING ARCHETYPES

When looking at change or upgrade of heating systems, knowing if a dwelling is connected to the gas grid can influence the final decision. A dataset published by BEIS provides information regarding the number of dwellings connected to the gas network at LSOA level [37]. However, there is no direct link between the archetypes defined and their connection to the gas grid. For instance, flats equipped with gas boilers are connected to the gas network but flats using resistance heaters may or may not be connected. Hence few assumptions have been made:

- All dwelling using oil/solid fuel boilers are not connected to the gas grid.
- All detached dwelling using resistance heating are not connected to the gas grid.
- The rest of the dwellings connected to the gas network are proportionally distributed between semi-detached dwellings, terraced dwellings and flats using resistance heating.

C. Calculation of linear heat density by LSOA

The linear heat density was estimated for each LSOA by using the length of the local road network[2] as a proxy of the length of a hypothetical heat distribution network.

D. Assumptions and input parameters to the optimisation model

Table 3 shows the sources of the values and sources of the data used in the optimisation model.

Parameters	Values	Source
Incentives	See source	Domestic RHI 2018. No incentives for district heating were considered.
Fuel emissions	See source	[38]
Cost for reinforcement of the electricity grid £/kWh	227 £/kW peak over 30 years	Using the reference scenario from [39]
ADMD for ASHP, GSHP and resistance heating	1.7, 1.7 and 3.4	ASHP and GSHP: [40] Resistance heating: [41]
Discount rate	4%	

Table 3: Characteristics regarding fuel emissions, reinforcements of the electricity grid and investment

The costs and characteristics associated to the individual heating technology are shown in Table 4 and Table 5. Decommissioning costs are added to the investment costs to the new heating unit when relevant. For instance, the replacement of a gas boiler by a resistance heating system requires the decommission of a gas boiler which is estimated at £500 and the addition of a hot water storage estimated at £1,000. This would increase the investment cost from £1,500 to £3,000 for a flat. Hybrid heat-pumps are considered to supply 80% of the heating using a heat-pump and 20% using a gas boiler.

Technology	**Dwelling type**	**Capex [£/unit]**	**Fixed O&M (excluding elecricity) [£/year]**	**Technical lifetime [years]**	**Auxiliary electricity consumption [kWh/year]**	**Efficiency heat**	**Main fuel**
Gas boiler	Flat	2000	75	20	150	84%	Ngas
Gas boiler	Detached	4000	75	20	150	84%	Ngas
Gas boiler	Semi-detached	2650	75	20	150	84%	Ngas
Gas boiler	Terraced	2650	75	20	150	84%	Ngas
Resistance heating	Flat	1500	21	30	0	100%	Electricity
Resistance heating	Detached	3150	25	30	0	100%	Electricity
Resistance heating	Semi-detached	2024	21	30	0	100%	Electricity

[2] road network data© Crown copyright and database rights 2018 Ordnance Survey (100025252)

Resistance heating	Terraced	2024	21	30	0	100%	Electricity
ASHP air-water	Detached	8272	60	18	100	340%	Electricity
ASHP air-water	Semi-detached	7238	48	18	100	340%	Electricity
ASHP air-water	Terraced	7238	48	18	100	340%	Electricity
GSHP Borehole	Detached	13916	85	20	100	337%	Electricity
GSHP Borehole	Semi-detached	13200	85	20	100	380%	Electricity
Oil boiler	Flat	3100	100	20	140	84%	Oil
Oil boiler	Detached	5192	205.92	20	140	84%	Oil
Oil boiler	Semi-detached	3100	100	20	140	84%	Oil
Oil boiler	Terraced	3100	100	20	140	84%	Oil
Biomass boiler	Detached	5984	429.44	20	240	82%	Biomass
Biomass boiler	Semi-detached	5984	429.44	20	240	82%	Biomass
Biomass boiler	Terraced	5984	429.44	20	240	82%	Biomass
Biomass boiler	Flat	5984	429.44	20	240	82%	Biomass
Hybrid HP	Detached	7333	96	12	110	289%	Hybrid
Hybrid HP	Semi-detached	7333	96	12	110	289%	Hybrid
Hybrid HP	Terraced	7333	106	12	110	289%	Hybrid

Table 4: Costs and technical parameters of individual technology [42], [8] and [43]

Action	**EAC [£]**	**Cost [£]**
decommission/replacement boiler	45	500
Replace/ upgrade / decommission (wet) heat emitters	36	400
District heating substation House	462	7218
District heating substation Flat	296	4621
Hot water storage	90	1000

Table 5: Decommissioning costs table [8] and the report “Hertfordshire Renewable and Low Carbon Energy Technical Study” from AECOM

The costs related to the production of heat for district heating are shown in Table 6. Assumption for feed-in tariff for electricity is that CHPs can sell electricity at a rate 30% lower than the retail price.

Technology	Technical lifetime [years]	Specific investment [£/MW]	Fixed O&M [£/MW/year]	Variable O&M [£/MWh] or [£/MWh/km] (excl. fuel costs)	Auxiliary electricity consumption [MWh/MWh_thermal]	Efficiency heat	Efficiency electricity
Natural gas boiler	25	52800	1716	0.88	0.0014	97%	0
Heat-pump	25	616000	1760	1.584	0.02	500 %	0
Waste heat	40			0.088	0.02	100 %	0
Natural gas CHP unit 1	25	889778	25784	3.872	0	45%	35%

Table 6: Costs and technical parameters of heat supply technology for district heating [44] and [24].

REFERENCES

[1] "2011 Census - Office for National Statistics." https://www.ons.gov.uk/census/2011census (accessed Aug. 23, 2019).

[2] "Net Zero-The UK's contribution to stopping global warming," Committee on Climate Change, May 2019. Accessed: May 13, 2019. [Online]. Available: https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf.

[3] "Carbon Footprint of Heat Generation," Houses of Parliament Parliamentiary Office Of Science and Technology, May 2016. Accessed: Jan. 18, 2018. [Online]. Available: http://researchbriefings.files.parliament.uk/documents/POST-PN-0523/POST-PN-0523.pdf.

[4] "Energy Consumption in the UK (ECUK) 2019 Data Tables," Department for Business, Energy & Industrial Strategy, 2019. [Online]. Available: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk.

[5] "Public reports and data: Domestic RHI," *Ofgem.gov.uk*, Jun. 07, 2016. https://www.ofgem.gov.uk/environmental-programmes/domestic-rhi/contacts-guidance-and-resources/public-reports-and-data-domestic-rhi (accessed Apr. 12, 2018).

[6] "Future energy scenarios," National Grid ESO, Jul. 2019. Accessed: Sep. 30, 2019. [Online]. Available: http://fes.nationalgrid.com/media/1409/fes-2019.pdf.

[7] S. Paardekooper *et al.*, "Heat Roadmap United Kingdom : Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps," Oct. 2018, Accessed: Nov. 30, 2018. [Online]. Available: http://vbn.aau.dk/en/publications/heat-roadmap-united-kingdom--quantifying-the-impact-of-lowcarbon-heating-and-cooling-roadmaps(97ba1469-8cb8-40fd-b0ed-3f2d25c866f7).html.

[8] "Analysis of alternative UK heat decarbonisation pathways," Imperial College London. Accessed: Nov. 30, 2018. [Online]. Available: https://www.theccc.org.uk/publication/analysis-of-alternative-uk-heat-decarbonisation-pathways/.

[9] C. Calderón, C. Underwood, J. Yi, A. Mcloughlin, and B. Williams, "An area-based modelling approach for planning heating electrification," *Energy Policy*, vol. 131, pp. 262–280, Aug. 2019, doi: 10.1016/j.enpol.2019.04.023.

[10] F. Jalil-Vega and A. D. Hawkes, "Spatially resolved model for studying decarbonisation pathways for heat supply and infrastructure trade-offs," *Appl. Energy*, vol. 210, pp. 1051–1072, Jan. 2018, doi: 10.1016/j.apenergy.2017.05.091.
[11] "The potential for recovering and using surplus heat from industry," Element energy for DECC, 2014. Accessed: May 31, 2018. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/294900/element_energy_et_al_potential_for_recovering_and_using_surplus_heat_from_industry.pdf.
[12] S. D. Watson, K. J. Lomas, and R. A. Buswell, "Decarbonising domestic heating: What is the peak GB demand?," *Energy Policy*, vol. 126, pp. 533–544, Mar. 2019, doi: 10.1016/j.enpol.2018.11.001.
[13] F. Jalil-Vega and A. D. Hawkes, "The effect of spatial resolution on outcomes from energy systems modelling of heat decarbonisation," *Energy*, vol. 155, pp. 339–350, Jul. 2018, doi: 10.1016/j.energy.2018.04.160.
[14] "Lower and Middle Super Output Areas gas consumption," *GOV.UK*. https://www.gov.uk/government/statistics/lower-and-middle-super-output-areas-gas-consumption (accessed Aug. 16, 2019).
[15] P. I. Knight, H. Iorwerth, and D. S. Lannon, "Re-Energising Wales Project Work Package 1 – Half-Hourly Energy Demand Profiles For Wales For 2016," p. 55.
[16] "AddressBase premium," Ordnance Survey, Wales, 2017.
[17] B. Möller, E. Wiechers, U. Persson, L. Grundahl, and D. Connolly, "Heat Roadmap Europe: Identifying local heat demand and supply areas with a European thermal atlas," *Energy*, vol. 158, pp. 281–292, Sep. 2018, doi: 10.1016/j.energy.2018.06.025.
[18] P. E. Dodds, "Integrating housing stock and energy system models as a strategy to improve heat decarbonisation assessments," *Appl. Energy*, vol. 132, pp. 358–369, Nov. 2014, doi: 10.1016/j.apenergy.2014.06.079.
[19] D. Scamman *et al.*, "Heat Decarbonisation Modelling Approaches in the UK: An Energy System Architecture Perspective," *Energies*, vol. 13, no. 8, Art. no. 8, Jan. 2020, doi: 10.3390/en13081869.
[20] E. Popovski, T. Fleiter, H. Santos, V. Leal, and E. O. Fernandes, "Technical and economic feasibility of sustainable heating and cooling supply options in southern European municipalities-A case study for Matosinhos, Portugal," *Energy*, vol. 153, pp. 311–323, Jun. 2018, doi: 10.1016/j.energy.2018.04.036.
[21] S. Ben Amer-Allam, M. Münster, and S. Petrović, "Scenarios for sustainable heat supply and heat savings in municipalities - The case of Helsingør, Denmark," *Energy*, vol. 137, pp. 1252–1263, Oct. 2017, doi: 10.1016/j.energy.2017.06.091.
[22] E. Popovski, A. Aydemir, T. Fleiter, D. Bellstädt, R. Büchele, and J. Steinbach, "The role and costs of large-scale heat pumps in decarbonising existing district heating networks – A case study for the city of Herten in Germany," *Energy*, vol. 180, pp. 918–933, Aug. 2019, doi: 10.1016/j.energy.2019.05.122.
[23] B. Möller, E. Wiechers, U. Persson, L. Grundahl, R. S. Lund, and B. V. Mathiesen, "Heat Roadmap Europe: Towards EU-Wide, local heat supply strategies," *Energy*, vol. 177, pp. 554–564, Jun. 2019, doi: 10.1016/j.energy.2019.04.098.
[24] S. Frederiksen and S. Werner, *District Heating and Cooling*. Studentlitteratur AB, 2013.
[25] U. Persson and S. Werner, "Heat distribution and the future competitiveness of district heating," *Appl. Energy*, vol. 88, no. 3, pp. 568–576, Mar. 2011, doi: 10.1016/j.apenergy.2010.09.020.
[26] "Technology Data for Energy Transport," Energinet and Danish Energy Agency, Dec. 2017. Accessed: Nov. 21, 2018. [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_energy_transport_dec_2017_1.pdf.
[27] J. Cox, "The Potential and Costs of District Heating Networks," p. 152, 2009.

[28] W. E. Hart *et al.*, *Pyomo–optimization modeling in python*, Second., vol. 67. Springer Science & Business Media, 2017.
[29] W. E. Hart, J.-P. Watson, and D. L. Woodruff, "Pyomo: modeling and solving mathematical programs in Python," *Math. Program. Comput.*, vol. 3, no. 3, pp. 219–260, 2011.
[30] "Energy Performance of Buildings Data England and Wales," Ministry of Housing, Communities and Local Government. Accessed: Aug. 23, 2019. [Online]. Available: https://epc.opendatacommunities.org/login.
[31] "Beyond average consumption - Development of a framework for assessing impact of policy proposals on different consumer groups," Centre for sustainable energy, Mar. 2014. Accessed: Aug. 16, 2019. [Online]. Available: https://www.cse.org.uk/downloads/reports-and-publications/policy/beyond_average_consumption_update_2014.pdf.
[32] "Updated energy and emissions projections: 2017," *GOV.UK*. https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2017 (accessed Aug. 01, 2019).
[33] "Fuel prices and Carbon factors," *Energy Saving Trust*, 2018. https://www.energysavingtrust.org.uk/about-us/our-calculations (accessed Oct. 02, 2019).
[34] M.-A. Millar, N. M. Burnside, and Z. Yu, "District Heating Challenges for the UK," *Energies*, vol. 12, no. 2, Art. no. 2, Jan. 2019, doi: 10.3390/en12020310.
[35] O. Pasichnyi, J. Wallin, F. Levihn, H. Shahrokni, and O. Kordas, "Energy performance certificates — New opportunities for data-enabled urban energy policy instruments?," *Energy Policy*, vol. 127, pp. 486–499, Apr. 2019, doi: 10.1016/j.enpol.2018.11.051.
[36] AECOM Building Engineering, "Energy Demand Research Project: Early Smart Meter Trials, 2007-2010," UK Data Service, 2018.
[37] "LSOA estimates of households not connected to the gas network," *GOV.UK*. https://www.gov.uk/government/statistics/lsoa-estimates-of-households-not-connected-to-the-gas-network (accessed Aug. 23, 2019).
[38] "Greenhouse gas reporting: conversion factors 2018," BEIS, 2018. Accessed: Dec. 01, 2019. [Online]. Available: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2018.
[39] "Managing the future network impact of electrification of heat," Delta Energy & Environment, Jun. 2016.
[40] J. Love *et al.*, "The addition of heat pump electricity load profiles to GB electricity demand: Evidence from a heat pump field trial," *Appl. Energy*, vol. 204, no. Supplement C, pp. 332–342, Oct. 2017, doi: 10.1016/j.apenergy.2017.07.026.
[41] M. (327173) Jones, "Framework for Design & Planning of LV Housing Developments, including U/G Networks and Associated HV/LV S/S," no. 7, p. 31.
[42] "Technology Data for Individual Heating Installations," Energinet and Danish Energy Agency, Mar. 2018.
[43] "Electrification of Heat and the Impact on the Scottish Electricity System," Delta Energy & Environment, Mar. 2016. [Online]. Available: https://www.climatexchange.org.uk/media/1897/electrification_of_heat_and_impact_on_scottish_electricity_system_-_final_report1.pdf.
[44] "Technology Data for Energy Plants for Electricity and District heating generation," Energinet and Danish Energy Agency, Aug. 2016. Accessed: Aug. 21, 2019. [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_el_and_dh_-_aug_2016_upd_oct18.pdf.