

Bristol net zero by 2030: Heat decarbonisation method report

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1. Summary

The objective of the heat analysis is to identify the least-cost approach to decarbonising space and water heating demand for all the buildings in (and around, to capture cross-boundary opportunities) Bristol. The modelling assumes that the options available are:

- heat networks in which the supply plant is a large air-source (ASHP) or water-source (WSHP) heat pump.
- ASHPs on individual buildings
- external wall insulation where the building is suitable

The scale and complexity of this question is apparent in Figure 1.1, which shows all the buildings, roads and paths within the Bristol city boundary.

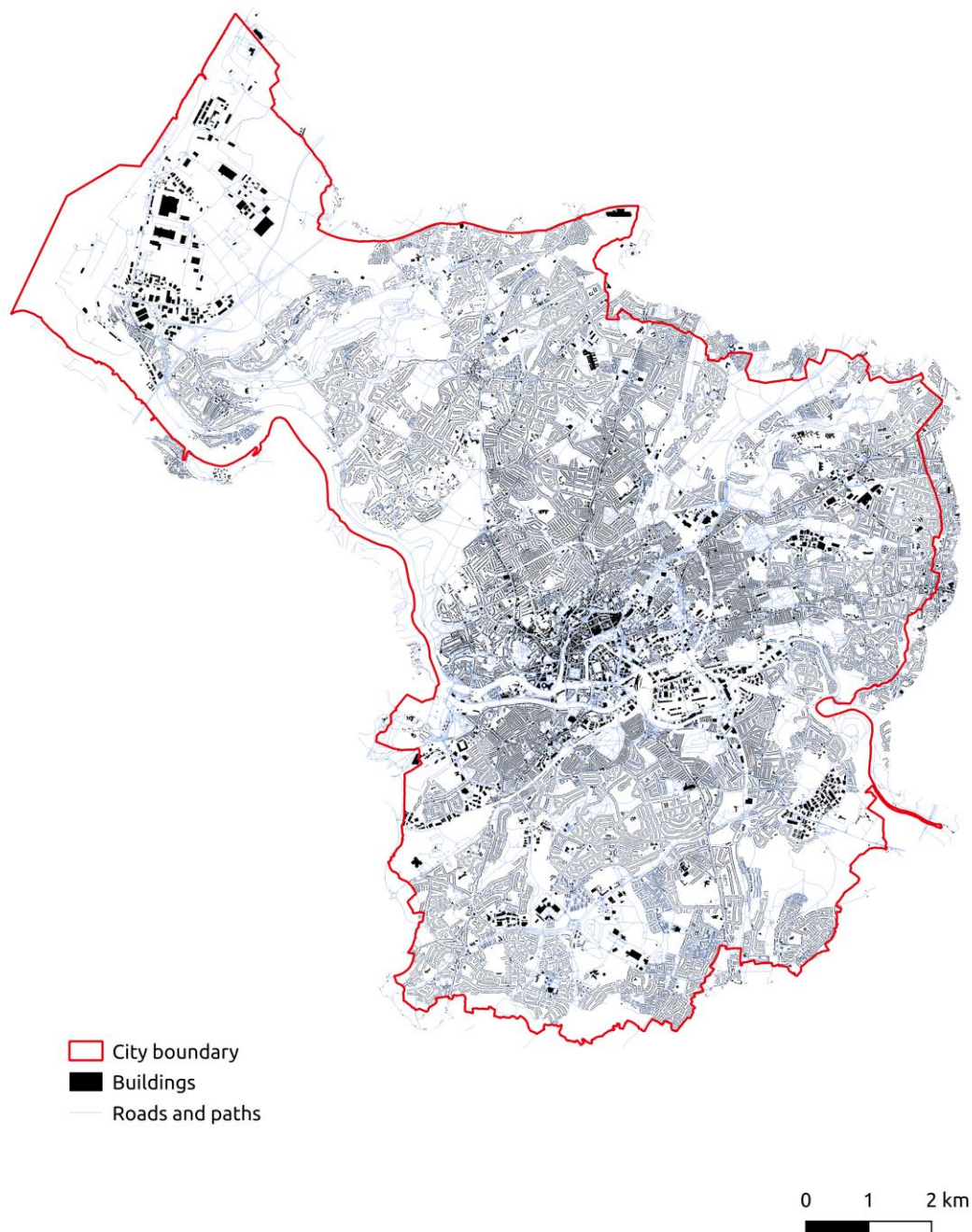


Figure 1.1: Buildings, roads and paths in Bristol.
Contains OS data: Crown copyright and database rights 2019 Ordnance Survey (100023406)

The list of options is based on the following assumptions:

- grid electricity will be zero-carbon by 2030
- limited biomethane and zero-carbon hydrogen resources will not be distributed directly to buildings
- most solid-walls have not been insulated

- most cavity walls and lofts have already been insulated
- it is safe to ignore other forms of insulation
- work is needed to identify waste-heat resources suitable as inputs to heat networks; in the meantime the fall-back assumption is that water-source heat pumps are used

The question is formulated as an optimisation problem, in which we want to minimise the total cost of meeting the heat demand of all the buildings in the city, using the measures listed above. We use our THERMOS optimisation model^{1,2,3,4} to solve the problem. However THERMOS cannot handle problems on the scale of 160,000 buildings, so we first divide the buildings into about 200 spatial clusters, each of which contains around 1000 buildings: at this scale, THERMOS can identify good solutions in a few minutes to a few hours.

For each cluster, the model selects a heat supply plant location close to the centre of the demand density for that cluster; the optimiser is then free to decide how best to satisfy the heat demands for all the buildings in the cluster, with the options being a network supplied from the chosen plant location (serving some or all of the buildings); individual heat pumps in some or all of the buildings; and in parallel with the supply choice, the model can install (a variable amount of) EWI if the building is suitable.

¹The THERMOS web application is available for free at <https://tool.thermos-project.eu>

²Detail on the THERMOS heat network model calculations is here: <https://tool.thermos-project.eu/help/calculations.html>

³Detail on THERMOS network optimisation formulation is here: <https://tool.thermos-project.eu/help/formulation.html>

⁴THERMOS heat demand estimation models: <https://tool.thermos-project.eu/help/demand-models.html>

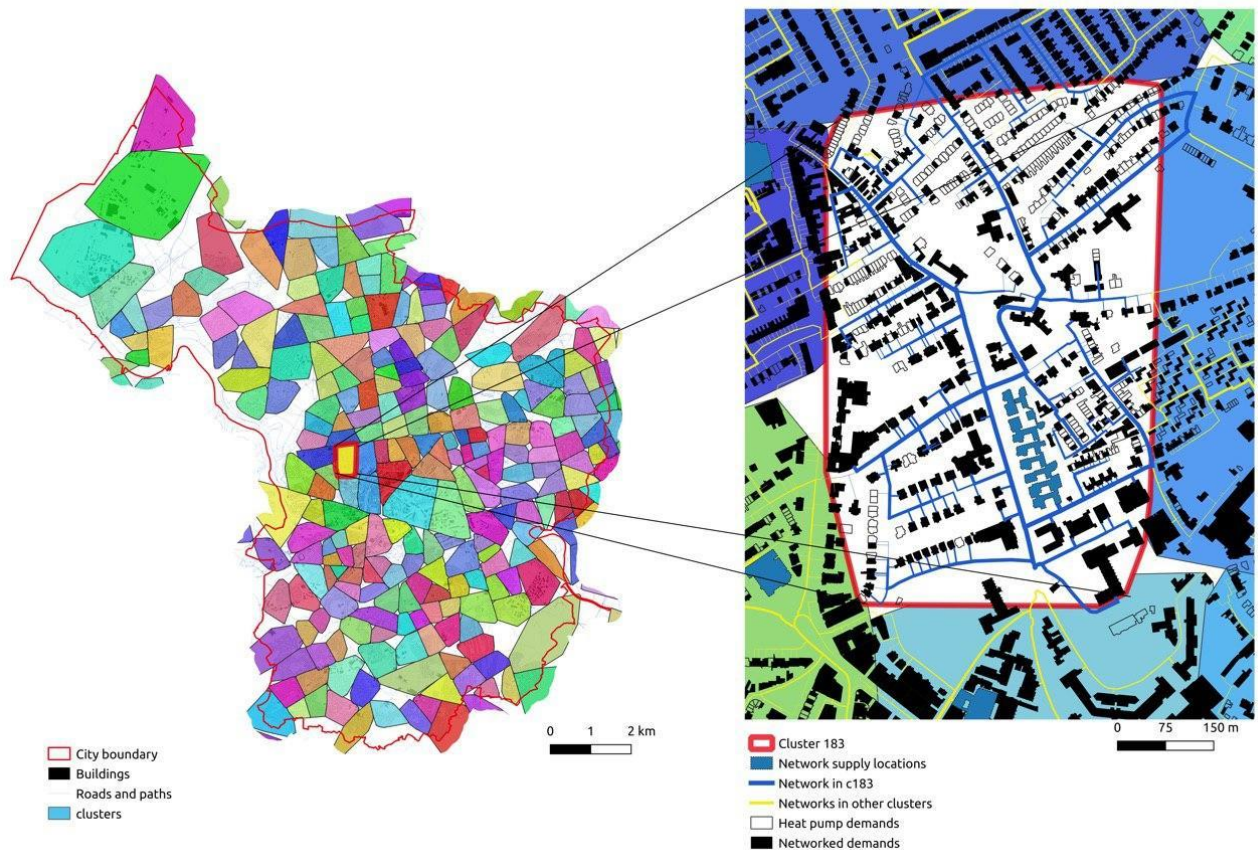


Figure 1.2: Method detail: result map for a single cluster.
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We have defined a set of scenarios under which the analysis is repeated. These are composed by varying some key parameters as follows:

- Discount rates: 0%, 2.5%
- Pipe costs: Low, Medium, High (see 5.1)
- Network supply: ASHP, WSHP (see 5.4)
- Insulation⁵: Optimum, Maximum (See 5.5)
- Electricity prices: Standard, plus two model runs with 50% increase to explore the effect on the optimal strategy of significantly higher costs for zero-carbon electricity (see 5.2)

This yields 26 scenarios, all of which are run against each of the ~200 spatial clusters, so that we have 26 results for each of the 160,000 buildings in the study area. On a 1000-CPU cluster, this analysis can be run in about 12 hours.

For each building, a result is:

- the choice of heating supply
- an amount (possibly zero) of external wall insulation
- the costs and benefits of these choices

⁵THERMOS handling of insulation: <https://tool.thermos-project.eu/help/insulation.html>

For each cluster, the result includes a sized and costed spatial description of a district heating network meeting the demand for the subset of buildings the optimiser decided to network. If there are no such buildings, then there will be no network. The network description includes the pipe routes and sizes, and the plant size.

We combine the results from each of the clusters, to produce:

- a summary table setting out the aggregate results at city-level:
- a spatial table associating the 26 results for each building with its building polygon
- a spatial table showing the district heating network pipe routes and supply locations for each cluster.

From this set of 26 variants, we selected a core scenario with the following attributes:

- discount rate: 0%
- pipe costs: Low
- network supply: water-source heat pumps
- insulation: optimum
- electricity prices: standard

The implications of this scenario drive the recommendations in the main report. See 6.2 for more detail.

2. Strengths and weaknesses

This approach has some strengths, and some weaknesses:

2.1. Strengths

- it is a building-and-street level model of an entire city, which automatically generates detailed representations of heat networks
- it uses an optimisation model to generate a least-cost solution for decarbonising the heat supply to every building in the city, including multiple heat supply options, network routing, and insulation
- this method can identify solutions which current heuristic methods (such as thresholding heat demand density estimates for relatively large areas) will miss- for example pockets of high heat demand density in otherwise low-density areas.
- the resulting spatial datasets provide a valuable and detailed input to subsequent implementation planning, which is another advantage over traditional methods

2.2. Weaknesses

- The model uses estimated rather than metered heat demands⁴, except for those buildings for which we have matched a Display Energy Certificate; the estimates are produced using a sophisticated model based on the 3D attributes of the buildings. But they are estimates nevertheless, and the least-cost solution is naturally sensitive to the amount of heat demand.
- Dividing the city up into small clusters is likely to have introduced some artefacts:
 - The cluster boundaries may in places separate buildings which would ideally belong in a single network. There may be improved clustering methods that separate buildings which

would be unlikely to belong to the same network, but we have only had time to use an off the shelf method.

- Even with 'ideal' cluster boundaries, there may be scale effects where a potential network exists spanning several clusters which would optimally capture more demand than individual networks within clusters
- The choice of supply locations for the clusters is also somewhat arbitrary- this is acceptable (and necessary) when solving a city-scale problem, but specific network proposals will need to be examined in more detail, and in doing so, plant location is a significant and often highly constrained decision.

3. Buildings and demand estimates

In brief:

- Buildings are from OS Mastermap Topographic Area "Buildings" theme polygons
- These are filtered to postally addressable locations using OS Addressbase Premium addressing data
- Demand estimates are from
 1. Display Energy Certificates where available, assuming a conversion efficiency of 85%
 2. CSE's THERMOS project space and water heating demand estimator⁴ where no DEC is available. This approach uses a model trained on ~30,000 building heat demand records from Copenhagen, with a correction applied to the space-heating component based on the ratio of the square roots of the annual total heating-degree-days for Bristol and Copenhagen. Peak demand is estimated from annual demand using a linear model trained on a large sample of halfhourly UK domestic gas meter data⁶.

4. Pipe routes

In brief:

1. Potential pipe routes are taken from OS Highways Network for the study area ("Roads " and "Paths")
2. These are intersected with OS Mastermap Topographic Area "Land" theme polygons, and OS Greenspace polygons, to classify route segments as hard- or soft-dig.
3. We then generate connections from the existing route network to each of the buildings
4. Finally we "node" the resulting network, dividing into a larger number of smaller segments such that no section contains an intersection. In other words, we cut the routes up at all intersections. This allows the THERMOS model construct efficient heat distribution networks which do not contain redundant segments.

5. Technology and fuel costs and assumptions

The least-cost optimisation modelling involves making a number of other assumptions about technology and fuel costs.

⁶EDRP smart meter dataset:

https://doc.ukdataservice.ac.uk/doc/7591/mrdoc/pdf/7591_edrp_accompanying_documentation.pdf

5.1. Pipe costs

Pipe costs are calculated by THERMOS in relation to their required peak capacity in kW. This is converted into a diameter based on a 30 degree flow/return temperature difference, and using standard assumptions about optimal flow rates and the specific heat capacity of water.¹

Finally, the cost of installing a metre of flow and return pipes of a given diameter is calculated as follows:

- Mechanicals (cost of purchasing the pipes): $50 + (700 * \text{diameter})^{1.3}$
- Civils (cost of installing pipes in the ground): $C + (D * \text{diameter})^{1.1}$ where C and D are taken from the table below, depending on the scenario and dig type

So for the "Low pipe costs" scenario, the civil costs per metre are calculated as follows:

- For soft-dig areas: $200 + (20 * \text{diameter})^{1.1}$
- For hard-dig areas: $500 + (750 * \text{diameter})^{1.1}$

The total cost per metre is then Mechanicals + Civils.

Three different sets of parameter values for the above pipe cost functions were developed in consultation with Bristol City Council's Energy Infrastructure Team, and technical experts at Sustainable Energy Limited. These are set out in table 5.1.1.

Table 5.1.1: Pipe cost function parameters by scenario and dig type

Scenario	Dig type	Fixed cost/m (C)	Variable cost £/m (D)
Low	Soft	200	20
Low	Hard	500	750
Med	Soft	250	250
Med	Hard	750	1120
High	Soft	300	300
High	Hard	1000	1500
All	Connector	450	450

5.2. Fuel price assumptions

Fuel	Price
Daytime bulk electricity	12p
Night-time bulk electricity	8p
Daytime domestic electricity	18.86p
Night-time domestic electricity	8.83p
Domestic gas	4.41p

5.3. Individual system parameters

System	Fixed cost £	Cost £/average kW	Cost £/peak kW	Cost p/kwh heat
Gas boiler	800	0	200	4.9p
GS Heat pump	8000	2496	0	5.9p
Storage heater		0		8.83p
AS Heat pump	3000	2496	0	7.9p

Assumptions:

- Heat pump cost/kw-*average* is derived from modelled value of £400/kW of installed size
 - This is done because THERMOS kWp includes hot water peak, but we want heating peak
 - The figure given 'converts' kW_a into kW_p of *space heat* by saying:
 - Space heat is 80% of total heat (expert judgement)
 - Space heat peak is 7.8 times space heat average (National Household Model (NHM))

In this:

- Fixed cost is for any installation
- Variable cost is per unit of peak capacity, so e.g. a typical combi-boiler is ~35kw
- Cost/kwh is for *delivered heat*, so for a typical non-varying efficiency this = input fuel price / efficiency

5.4. Plant parameters

These are parameters for supply of heat to the network at the energy centre.

Heat source	Fixed cost	Opex £/kw	Capex £/kw	Heat cost/kWh
WS Network HP	0	25	500	3.33p
AS Network HP	137759	0	434	3.9p + 0.15p

- Assuming:
 - No maximum size (we'll buy more plants)
 - For WS Network HP
 - WSHP at 70/40 network temperature, supply 12 deg
 - Fit says £0 + £500/kW
 - Electricity at 12p [this is the SEL value]
 - COP is *average* from SEL data, but looks OK

- ASHP
 - SEL data
 - 11 deg source temperature
 - Solid Energy devices
 - COP is average, and does have some spread which means error
 - Capex fit is good
 - Cost/kwh includes an opex/kwh (3.9p of electricity and 0.15p of opex); there is no opex/kwp
- Cost/kWh here is the cost to put 1kWh of heat into the network at the energy centre. It is *not* the cost of supplying 1kWh of heat to a network customer.

5.5. Insulation parameters

Insulation	Fixed cost £	Cost/m ²	Max. Reduction %	Area %
EWI	2500	65	38%	76%

- Assumptions:
 - Max reduction and area % from NHM:
 - proportion of wall getting EWI
 - Min. :0.1083
 - 1st Qu.:0.7162
 - Median :0.8000
 - Mean :0.7635
 - 3rd Qu.:0.8109
 - Max. :0.9330
 - Reduction in space and water heating (proportion) Min. :0.005776
 - 1st Qu.:0.346090
 - Median :0.404940
 - Mean :0.378146
 - 3rd Qu.:0.443742
 - Max. :0.590380

How these numbers work is:

- The model will choose to buy $X \text{ m}^2$ of insulation for a building
- This will cost: fixed cost + ($X * \text{cost/m}^2$)
- The effect will be to reduce the building's energy demand by a factor of

$(\text{reduction \%}) * (X / (\text{wall area} * \text{area \%}))$

To make this a bit more concrete, imagine a house with:

- 30MWh/yr heat demand
- External wall area of 200m²

If we say that EWI has:

- Fixed cost of £1000
- Variable cost of £25/m²
- Max. Reduction of 30%
- Area % of 75

We would look at the building and say:

- Insulatable area = $200 * 0.75 = 150$
- Energy saving for full insulation = $30 * 0.3 = 9\text{MWh/yr}$

Then the model could buy, for example 100 m² of insulation; this would cost £1000 + £25 * 100.

It would yield a reduction of $9 * 2/3 \text{ MWh/yr} = 6 \text{ MWh/yr}$ (because we covered 2/3 of the total insulatable area).

5.6. Network connection costs

Components	Fixed cost £	Variable cost £/kW
HIU and meter	1654	39.76

- These are in addition to the pipe connecting the building HIU to the network
- Direct connections for space heat would be cheaper, but are not likely to be favoured in Bristol

Connecting a building to the network involves installing a heat exchanger in the building among other things (which will also have a cost).

The model has a capital cost for this, which depends on the connection size.

6. Results of least-cost heat decarbonisation analysis

6.1. Scenario naming

26 different scenarios were modelled. The following naming convention was used to distinguish them:

- ifix means that the maximum possible amount of external wall insulation was installed on all suitable buildings, rather than the cost-optimal amount. Note that in the high-electricity-cost model runs, maximum insulation tends to be chosen as part of the least-cost solution.
- d_0 means discount rate = 0, d25 means discount rate = 2.5%
- p_L means Low pipe cost scenario, p_M means Medium pipe cost scenario, p_H means High

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pipe cost scenario (see 5.1 for more detail)

- s_ashp means the heat networks are supplied from an air-source heat pump, s_{wshp} means the plant is a water-source heat pump (see 5.4 for more detail)
- e_H means that the electricity prices set out in 5.2 were increased by 50% for these model runs
- So d_0-p_L-s_wshp-e_H means "Zero discount rate, Low pipe costs, heat networks supplied from water-source heatpumps, electricity costs 50% higher than standard"

6.2. Core scenario

Scenario d_0-p_L-s_wshp (zero discount rate, low pipe cost, water-source heat pump, standard electricity prices) was selected as the most appropriate scenario on which to base policy analysis and recommendations. The findings in our main report are based on this scenario. We chose it for the following reasons:

- Discount rate: the objective of the analysis is to identify the lowest cost long-term strategy for decarbonising space and water heating in Bristol. In the context of a climate emergency, and the need to decarbonise heat by 2030, we could see no justification for using a positive discount rate when accounting for future costs and benefits. Indeed, a case can be made for using a *negative* rate, given the risk that the marginal damage curve for cumulative emissions may not be linear. See also Footnote 13 on page 29 of the main report. Also note that the optimisation objective in the modelling is to minimise lifetime costs, not to maximise the NPV for a particular actor: this is a different question, more relevant to implementation planning than strategy development. The effect of a positive discount rate here would be to reduce the importance of operating and fuel costs over the 40 year timeframe- this tends to favour lower up-front cost solutions, even if they are more expensive in the long term.
- Pipe costs: the Low pipe costs scenario was chosen because
 1. there is consensus that heat networks pipe installation costs are relatively high in the UK, due to the limited rate at which they are currently being constructed. If networks are commissioned at the pace required, we would expect to see scale economies in construction costs. In this context the Low pipe cost scenario may actually be conservative.
 2. the modelling assumes that steel pipes are used throughout the networks; in practice however it is possible to use plastic pipes for the tertiary parts of the network, and this is significantly cheaper than the steel alternative
- Supply plant: water source heat pumps are more efficient and cost-effective than their air-source counterparts (see 5.4). We assume that Bristol's significant water-source opportunities will be exploited. These include the Severn estuary at Avonmouth; the river Avon running along the Avon Gorge; various water bodies within the city; extensive former mineworkings beneath the city.

The results for the core scenario are summarised below (costs are £ millions unless stated).

Table 6.2.1: Aggregate results for core scenario

Scenario	d_0-p_L-s_wshp
DH connections	67,689
HP installations	94,428
Insulation installations	72,785
DH heat supplied (GWh/y)	1,737
DH heat loss (GWh/y)	213
HP heat supplied (GWh/y)	724
Insulation total effect (GWh/y)	400
DH peak GW	1.5
HP GW	2.6
DH Present Cost	5,294
HP Present Cost	3,454
Insulation Present Cost	642
DH cost over 40y	5,294
HP cost over 40y	3,454
Insulation cost over 40y	642
Total cost over 40y	9,391
Total DH pipe capex	1,001
Total DH heat exchanger capex	200
Total DH supply capex	748

Total Heat Pump capex	584
DH unit cost of system (£)	0.076
HP unit cost of system (£)	0.119
DH unit price of heat (£)	0.037
HP unit price of heat (£)	0.079
DH % share of heat	61
Insulation % demand reduction	14
Total DH pipe length (km)	1,722

6.3. Summary of all scenarios

Table 6.3.1: Aggregate results for all scenarios (see accompanying spreadsheet file for full table)

scenario	DH count	HP count	Ins. count	Total cost £m (40y)
d_0-p_H-s_ashp	23,313	138,804	82,513	9,907
d_0-p_H-s_wshp	40,581	121,536	77,390	9,591
d_0-p_L-s_ashp	35,766	126,351	81,004	9,777
d_0-p_L-s_wshpe-H	125,532	36,585	81,578	11,797
d_0-p_L-s_wshp	67,689	94,428	72,785	9,391
d_0-p_M-s_ashp	29,184	132,933	81,841	9,850
d_0-p_M-s_wshpe-H	113,752	48,365	81,952	12,062
d_0-p_M-s_wshp	53,091	109,026	74,259	9,511
d_25-p_H-s_ashp	10,462	151,655	82,432	9,885
d_25-p_H-s_wshp	18,991	143,126	78,651	9,523
d_25-p_L-s_ashp	17,553	144,564	79,438	9,760

scenario	DH count	HP count	Ins. count	Total cost £m (40y)
d_25-p_L-s_wshpe-H	71,140	90,977	68,895	11,815
d_25-p_L-s_wshp	26,505	135,612	76,341	9,331
d_25-p_M-s_ashp	13,076	149,041	81,216	9,842
d_25-p_M-s_wshpe-H	55,009	107,108	72,429	12,056
d_25-p_M-s_wshp	22,096	140,021	77,810	9,441
ifix-d_0-p_H-s_ashp	20,597	141,520	85,070	9,883
ifix-d_0-p_H-s_wshp	37,551	124,566	85,070	9,549
ifix-d_0-p_L-s_ashp	33,174	128,943	85,070	9,772
ifix-d_0-p_L-s_wshp	61,071	101,046	85,070	9,395
ifix-d_0-p_M-s_ashp	25,145	136,972	85,070	9,833
ifix-d_0-p_M-s_wshp	46,752	115,365	85,070	9,492
ifix-d_25-p_H-s_ashp	10,186	151,931	85,070	9,862
ifix-d_25-p_H-s_wshp	13,841	148,276	85,070	9,537
ifix-d_25-p_L-s_ashp	13,750	148,367	85,070	9,759
ifix-d_25-p_L-s_wshp	20,300	141,817	85,070	9,360
ifix-d_25-p_M-s_ashp	11,423	150,694	85,070	9,825
ifix-d_25-p_M-s_wshp	16,841	145,276	85,070	9,460

6.4. Estimating impacts on heating bills

To estimate average annual fuel bills for households using heat pumps and heat networks, we used current electricity prices and the modelled 'supplied heat' price for the heat network. We have not attempted to predict future electricity prices.

For homes with heat pumps, we used the average electricity input required to produce the modelled heat requirement in the home (taking account of both the heat pump COP and any insulation installed) and multiplied it by the current average electricity unit price and added the average standing charge.

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For heat networked homes, we used the modelled price for supplied heat, and average heat demand for heat networked homes (after accounting for the effects of insulation). This assumes current average commercial prices for electricity (since the heat network will be supplied by a heat pump on commercial electricity tariffs)

To compare these results with the current cost of gas heating (to show the comparison with current practices), we took the average domestic gas heating bill (including the standing charge) as provided by Ofgem's latest data on domestic fuel costs and bills.

This suggests that, under the core scenario, average household heating bills will on average be 20% – 30% higher (c.£100- £150 at current prices) than current typical average costs with gas central heating. This will be partly offset by households avoiding the gas standing charge (typically £90-£100 per year) when they are no longer using a gas supply. See page 36 of the main report for further discussion.