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Costs of zero emissions heating in new build

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1 Executive summary

1.1 Aims

The Scottish Government has signalled its intention to develop new building standards that will ensure all new homes use zero emissions heating at the point of use from 2024. Similar requirements are also due to be phased in for non-domestic buildings. This report looks at the costs of delivering zero emissions heating in domestic and (as far as possible[1]) non-domestic new buildings. It identifies the factors that influence these costs and how they are split between different actors, including building developers, building owners and building users over the lifetime of a technology. Zero emissions heating is defined as zero emissions heating at *the point of use* throughout this work.

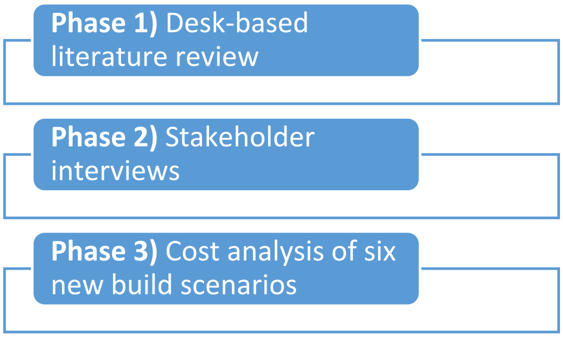

Figure 1: Three phases of research analysis used to inform the findings presented in this report

The work was conducted in three phases, as set out in Figure 1. Findings from the literature review and stakeholder interviews were used to inform assumptions for a cost analysis model, which was used to analyse six new build scenarios: Scenario 1: Private housing development; Scenario 2: Mixed-use build-to-rent development; Scenario 3: Social housing development; Scenario 4: Small-scale rural development; Scenario 5: Student accommodation; Scenario 6: Primary school.

The cost analysis considered six zero emissions heating technology options within the cost analysis (air source heat pumps

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[1] The majority of existing literature focuses on domestic as opposed to non-domestic buildings. This review considered both domestic and non-domestic new builds, however, greater focus was placed on domestic new build literature since there was insufficient time in this study to search for literature on the diverse range of non-domestic building archetypes that exist.

(ASHPs), ground source heat pumps (GSHPs), on-demand direct electric heating (dry system), direct electric heating (wet radiator system), new district heating network; connection to an existing district heating network), as well as building-level solar PV as an additional electricity source to feed into the selected electric heating system.

1.2 Key findings

Cost analysis

- In all six scenarios, the use of zero emissions heating technology options represented lifetime cost increases ranging from 25%-231% compared to the equivalent lifetime cost of heat supply using gas boilers.

- There is a significant difference in the cost optimum zero emissions heating solution, depending on whether it is considered in terms of capital expenditure (CAPEX), electricity running costs or lifetime costs. The 'cost-optimum' technology option for each scenario therefore depends on the commercial delivery model of the developer, for example, whether they are concerned with the full-lifetime cost of the technology (e.g. a build and operate delivery model), the CAPEX costs (e.g. a build-to-sell model), or running costs (e.g. a housing association seeking to reduce fuel poverty for tenants).

- Individual ASHPs appeared cost optimum on a lifetime cost basis in the scenarios with less dense developments (Scenarios 1, 3 and 4), offering lower lifetime costs than the other technologies including direct electric heating (For example, in the private development represented in scenario 1, the levelised lifetime cost of an ASHP £166/MWh, compared to £237/MWh for a GSHP and £208/MWh for a dry electric heating solution). Lifetime costs were significantly lower in the scenarios where it was assumed that new developments could connect to an existing district heating network (considered in Scenarios 5 and 6). A new district heating network also appeared cost-optimum in the high-density mixed-use development assumed in Scenario 2.

- Since grid constraint costs were excluded from the analysis, wet and dry electric heating options offered a significantly lower capital cost, but with higher electricity running costs. However, these capital costs would be expected to increase in areas with power grid constraints since direct electric heating options produce a greater electricity demand than other ZEH technology options and would require the most significant grid upgrades.

Stakeholder analysis

- The stakeholder interviews highlighted how the choice of which zero emissions heating technology to use in developments was driven by more than just cost considerations. Commercial delivery models and the role that a developer played in a development after construction (e.g. taking on an operation and maintenance role in energy services, objectives to minimise occupant energy bills, etc) were also key factors in technology choices for zero emissions heating.

- Delivering zero emissions heating was perceived as a significant change in existing development processes for some interviewees, and design and delivery processes were still being optimised and refined. There was greater evidence of innovation in the social housing sector. In this area policy drivers and the opportunities offered by zero emissions heating technologies to reduce costs to residents had led to development of compatible solutions and innovations ahead of new-build policy drivers such as the 2024 zero emissions heating standards.

- This study highlights a potential gap in the sector for energy service organisations to deliver technology options with higher capital costs but lower running costs (i.e. optimising use of lowest lifetime cost). Such organisations take a long-term view on the asset performance and are incentivised to optimise design, operation and maintenance over the lifetime of the system and thereby reduce whole life costs.

1.3 Recommendations

- Facilitate greater knowledge sharing from the social housing sector with the private house building sector. In the former piloting and innovation of different zero emissions heating technologies and trade-offs with energy efficiency have been going on for many years in new-build developments.

- The Scottish Government, the new-build development sector and the energy sector could consider where there are opportunities to support the development of new delivery models that can facilitate the delivery of the lowest lifetime cost technology options across Scotland, whilst factoring in running costs to building occupants. This could include expanding the role for Energy Service Companies.

Further research

Research and evidence gathering in a number of areas may be useful in providing further insight into the cost implications of forthcoming legislation on zero emissions heating in new builds:

- Understanding how the inclusion of grid constraint upgrade costs would influence a cost comparison between technologies for the six scenarios. This was an area of significant concern for the new-build developers interviewed as part of the research. We are aware that the Scottish Government has commissioned a parallel study led by Ricardo Energy & Environment (Ricardo Energy & Environment, 2020) to explore the impacts of electricity network constraints and the 2024 New Build Heat Standard. There is an opportunity to combine the findings of these two studies to explore the full costs of zero emissions heating in new build for different energy system actors.

- Further analysis to explore the lifetime costs of reaching higher energy efficiency levels within buildings vs. supplying zero emissions heating. The analysis conducted here to consider the costs of reaching Passivhaus standards required a range of high-level assumptions that should be considered as an initial indication of results and would benefit from further refinement.

Contents

Acknowledgements

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Nomenclature and key definitions

ASHP – Air source heat pump

CAPEX – Capital expenditure

COP – Coefficient of performance, used in connection to the performance of heat pumps

DH – District heating

GSHP – Ground source heat pump

kW - Kilowatt

kWh – Kilowatt Hour

Levelised Lifetime Cost – the undiscounted whole lifetime cost of a technology (including Capex, electricity costs, maintenance costs and replacement costs over a 40 year lifetime) divided by the total energy demand for the scenario over the lifetime (£/kWh)

OPEX – Operational expenditure

Passivhaus -: "A Passivhaus is a building in which thermal comfort can be achieved solely by post-heating or post-cooling the fresh air flow required for a good indoor air quality, without the need for additional recirculation of air." - Passivhaus Institut (PHI). The performance target for such a building’s space heating demand is ≤ 15 kWh/m^2/year.

REPEX – Replacement Expenditure –costs are compared across over a set lifetime of 40 years for all technologies in the study. The REPEX costs represent the expenditure required to replace part or all of a technology in order to enable it to continue to deliver heat over this time period. (These costs are assumed to be spread evenly across the lifetime and accounted for on an annual basis)

SAP – Standard Assessment Procedure - the methodology used by the Government to assess and compare the energy and environmental performance of dwellings

WSHP – Water source heat pump

ZCB – Zero carbon building

2 Introduction

2.1 New-build zero emissions homes – analysis of the policy context

In April 2019, the Scottish Government declared a Climate Emergency and increased its carbon reduction targets to achieve net zero greenhouse gas emissions by 2045 (Climate Change (Emissions Reduction Targets) (Scotland) Act 2019). A key challenge for meeting these ambitions will be delivering zero emissions heating (space and hot water) in buildings, which accounts for 47% of Scotland's carbon emissions from the energy system[2], with a large proportion supplied by natural gas boilers.

Delivering zero emissions heating in new buildings should, theoretically, be one of the simpler actions for meeting the heat decarbonisation challenge; it offers an opportunity to design in energy efficiency and low carbon heat supply technologies from the outset without the added complication and costs of retrofitting[3]. Ensuring zero emissions heating in all new buildings would also provide an opportunity for supply chains and consumers to build experience of energy efficiency and low carbon supply technologies, and potentially catalyse their wider uptake in retrofit situations. The Scottish Government has signalled its intention to develop new regulations that will ensure all new homes use zero emissions heating at the point of use from 2024. Similar requirements will be also be phased in for non-domestic buildings[4]. Understanding the wider consequences of this policy implementation is critical to ensuring a joined-up approach across policy areas.

There are a range of challenges facing new buildings to achieve these goals for zero emissions heating, seeking to find a cost-effective balance between minimising heat demand through a combination of fabric energy efficiency, building-level heat generation and larger area infrastructure approaches (e.g. district heating and ambient temperature networks, which also benefit from being able to provide cooling). These solutions each have associated lifecycle costs including capital, operational and replacement expenditure (CAPEX, OPEX and REPEX)[5]. The apportioning of these costs is critical to create an affordable and commercially viable proposition for building (and wider infrastructure) developers, but also requires careful consideration for how to make them affordable to customers. Understanding the cost implications of new build zero emissions heating is complex and requires consideration of multiple factors:

- There is a wide range of technology options and possible combinations for delivering zero emissions heating (from fabric solutions such as Passivhaus design through to use of renewable heat supply[6]). Finding the optimum balance of energy efficiency solutions and low carbon heat supply technologies is dependent on

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[2] Scottish Government (2015), Heat Policy Statement - Towards Decarbonising Heat: Maximising the Opportunities for Scotland

[3] A study by Currie & Brown for the Committee on Climate Change (2019) found that the costs of achieving higher standards via retrofit are three to five times higher than for new buildings (Currie & Brown, 2019, '*The costs and benefits of tighter standards for new buildings*')

[4] Scottish Government News Article 'New build homes to be more energy efficient' (05/01/2020) https://www.gov.scot/news/new-build-homes-to-be-more-energy-efficient/

[5] See 'Nomenclature and key definitions' for more information.

[6] Throughout this report we use the term 'technologies' to refer to both energy efficiency and heat supply solutions to deliver zero carbon heating.

numerous factors including the geographic characteristics of the development site; the scale of the development; and the preferences of the developer, site owner and intended users.

- The choice of technology is dependent on the type of development taking place. The building type(s) and size, development density, scale, local electricity grid capacity, location and availability of low carbon heat sources are all influential factors that need to be considered in technology selection.
- The business case and commercial delivery model for the development determine where the responsibility falls for the capital costs and operating and maintenance costs of the infrastructure and resulting buildings. These costs could be borne by the developer, or in some cases passed on to the building user through energy costs or building purchase.
- Costs of low carbon technologies are still uncertain and are likely to change as supply chains develop, new markets grow and enhanced skills and best practices in design and installation are established.

This work seeks to explore the cost impacts of the proposed shift to zero emissions heating in new builds, both in terms of any changes in capital costs that arise, and also the lifetime costs including impacts on end-user bills[7]. In addition, in the domestic sector, the Scottish Government's policy initiatives are seeking to support the creation of affordable homes through the More Homes Scotland approach[8]. A key consideration is therefore how any additional capital cost that could result from a shift to zero emissions heating, at least during the transitional phase, might impact on the viability of existing commercial delivery models for private and social housing developers.

2.2 The research aim

This research aims to understand costs of delivering zero emissions heating in domestic and (as far as possible) non-domestic new buildings, identifying the factors that influence this cost and how it is split between different actors including building developers, building owners and building users over the lifetime of the technology.

As per the scope set by the project steering group, zero emissions heating is defined as zero emissions heating *at the point of use* throughout this work.

The work has sought to address the following objectives in order to achieve the research aim:

1) To qualitatively understand the factors which influence the cost of meeting zero emissions heating in new builds (social, organisational, economic and technical) through a desk-based literature review and stakeholder interviews.
2) To characterise the commercial delivery models used by actors leading new build developments and their implications for the split of costs between developers, building owners and building users of installing, operating and maintaining these technologies throughout their lifetime.
3) To compile a database of the current range of capital, operation and maintenance costs for relevant zero emissions heat technologies over their lifetimes.
4) To quantify the costs to different actors of zero emissions heating in new buildings for a range of six representative scenarios (see section 3 on Methodology for

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[7] Specific consideration of the important question of fuel poverty impacts lies outside of the scope of this study, however, this would be an important area requiring further research.

[8] Scottish Government webpage 'More Homes' (accessed 30/08/2020) https://www.gov.scot/policies/more-homes/

details) for domestic and non-domestic new build developments in Scotland in comparison to current building and operating costs in similar scenarios.

This research will help to identify potential opportunities for reducing costs for delivering zero emissions heating in new builds in Scotland, offering insights in how and why decisions are made, and the impact of policy and regulations in influencing this.

3 Methodology

The research was completed in three phases: Phase 1) a desk-based literature review (conducted by the team at the University of Edinburgh), and Phase 2) stakeholder interviews (which address research objectives 1, 2 and 3 above); and Phase 3) a cost analysis of a representative selection of new build scenarios (to address research objective 4). The approach used for each of these phases is set out below.

3.1 Literature review

A desk-based literature review was undertaken by the University of Edinburgh team to consider both academic and grey literature from Scotland, the UK and internationally to summarise the existing evidence in relation to a primary question:

- *What are the current estimates and assumptions for the capital, operation and maintenance costs for the technologies considered in this study? And how might these costs be expected to change over time?*

Additionally, several sub-research questions were explored less extensively:

- *What factors can influence the cost of meeting zero emissions heating in new builds?*
- *What are the perceived barriers and risks with regards to costs of delivering zero emissions heating in new build developments?*
- *What commercial delivery models are used by actors leading new build developments?*

The findings from the literature review are presented in Section 0.

3.2 Stakeholder interviews

Interviews were conducted with ten Scottish stakeholders representing both new build developers and low carbon technology supply chain actors. The interviewees represented four of the six scenarios considered within this study (omitting a small-scale housing developer and a local authority-owned primary school). Interviewees were selected because of their experience of delivering or planning to deliver low or zero emissions heating in new build developments:

- Cala Homes (housing developer)
- Carrier (heat pump supplier)
- Eildon Housing Association (social housing provider)
- Hjaltland Housing Association (social housing provider)
- Homes for Scotland (house builders members association)
- Kensa Heat Pumps (heat pump supplier)
- SSE Enterprise (district heating developer and operator)
- Scottish Federation of Housing Associations

- Unite students (Student accommodation developer and operator)
- Winchburgh Developments (Land developer)

The interviews explored three overarching themes with each of the interviewees, using examples from their past experiences delivering zero / low emissions heating in new build developments (both domestic and non-domestic):

1. Commercial delivery models used to deliver new build developments and how this affected the choice of technology
2. Current estimates and assumptions for the capital, operation and maintenance costs for zero emissions heat technologies (which are reflected in the scenario analysis assumptions)
3. Factors that influence the cost of meeting zero emissions heating in new builds (social, organisational, economic and technical)

Findings from these interviews were used to supplement and refine the findings of the literature review, as well as inform the assumptions made in the cost analysis. A summary of the key findings are presented in Section 5.

3.3 Cost analysis

There are numerous factors that influence the choice of technology solutions for zero emissions heating, and the corresponding costs. This project considered six scenarios for a range of new build developments: 1) private housing development; 2) mixed-use development; 3) social housing development[9]; 4) small-scale rural development; 5) student accommodation; 6) primary school. The scenarios were defined to explore the different impacts of variations in the followings aspects of new build developments:

1) building archetypes.
2) the density of the new build development
3) size of the new build development (stand-alone / small / medium / large)
4) type of building-use (domestic / non-domestic / mixed-use)
5) spatial archetype of the development (how the development fits within its wider geographical context e.g. types of surrounding buildings and how they may influence the solution within the site).

The assumptions made in the six scenarios are described in detail in Table *1*. A cost analysis was undertaken for each scenario to compare the costs of different zero emissions heating technologies over a period of 40 years[10]. **Error! Reference source not found.** summarises the analysis process for exploring the costs of zero emissions heating in each scenario.

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[9] This study considers social housing as a stand-alone scenario (Scenario 3); however, it should be noted that new build social housing is often also a feature of larger private developments through an obligation on the developer. The analyses considered for Scenarios 1 (private housing development) and Scenario 2 (mixed-use development) therefore have relevance for considering the cost implications for the electricity running costs for residents in the affordable housing within these developments.

[10] 40-year lifetime period was used since this is the industry standard for longer lifetime technologies such as district heating. This enables comparison of technologies, with technologies assumed to be replaced like-for-like at the end of their lifetime.

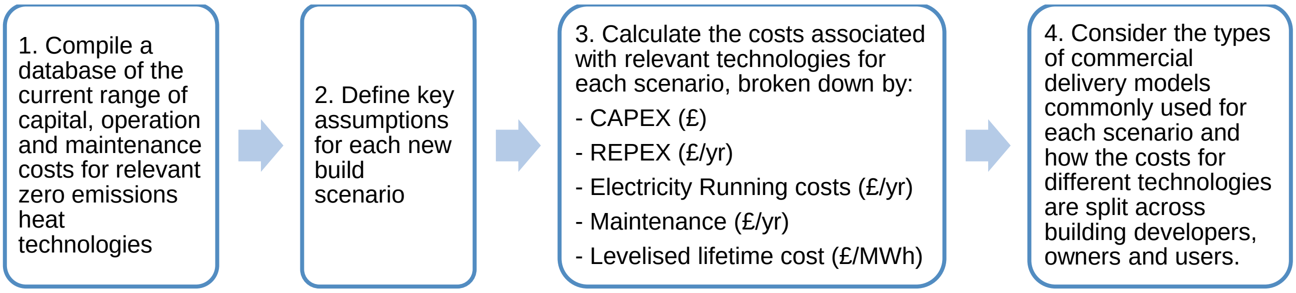

Figure 2: Process for comparing the costs of each zero emissions heating technology in each new build scenario

Note: the levelised lifetime cost of heat is a key measure used within the analysis. This is defined as the undiscounted whole lifetime cost of a technology (including Capex, electricity running costs, maintenance costs and replacement costs over the 40 year lifetime) divided by the total energy demand for the scenario over the lifetime (£/kWh). This is used as a key metric for comparison across the technologies. However, certain commercial delivery models of new build developers will be more concerned with specific parts of this lifetime cost (e.g. private house builder may be particularly focused on the CAPEX costs, whereas a social housing developer may be most concerned with the affordability of the running costs of a technology for tenants). The results must therefore be considered in the context of the specific scenario and commercial delivery model of the developer.

Zero emissions heating technology options

For each scenario, we considered the following technology options[11]:

- **Air source heat pumps (ASHPs)** - Smaller buildings are assumed to have individual air-to-water heat pump units with individual hot water tanks which serve as a form of thermal store. Flats and multi-use buildings are assumed to have one communal unit per block, sized at 75% of the peak heat demand across the building as a whole[12] (allowing for variation in peak heat demand across the building)[13]. Thermal storage is assumed at a communal-level for the building as a whole.
- **Ground source heat pumps (GSHPs)** – assuming borehole GSHPs at a depth of 100-200m, extracting heat at 10-20°C (similar to ASHPs, all buildings are assumed to have individual units, except flats and multi-use buildings, which are assumed to have one communal unit per block)
- **On-demand direct electric heating, dry system -** comprising wall-mounted electric radiators[14].

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[11] Hydrogen was out of scope of the analysis, since this would require sufficient hydrogen production and distribution, not yet available or proven at scale.

[12] Peak heat demand assumption based upon authors' experiences of heating system design for similar developments, and may vary in practice.

[13] The assumption of a communal heat pump for blocks of flats and multi-use buildings was deemed appropriate for the scenarios considered within the study since this only affected build-to-rent situations. In practice, individual heat pumps for each user may be used to remove the need for individual heat metering and billing. This would result in higher costs for these options.

[14] Storage heaters were not included within the scope of the research as the cost analysis model considered only flat-rate electricity tariffs. A further area of research would be to explore the impact of variable rate electricity tariffs on the costs of ZEH options.

- **Direct electric heating**, **wet radiator system** - supplied by water heated in an electric boiler, supported by thermal storage in the form of a hot water tank.
- **New district heating (DH) network** - assumed low temperature hot water network, supplied by a heat pump and supported by electric boilers to meet peak loads and to act as back up supply[15]. This was considered for Scenarios 1, 2, 3 and 4 only.
- **Connection into an existing district heating network** – This technology option assumes an existing heat network is present. Connection costs for the development assume an additional length of 50m of pipework from the existing network, with a substation sized on the kW rating of connected building. This option was considered for Scenarios 5 and 6, since these represented single building developments.
- **Building-level solar PV** as an additional electricity source to feed into the selected electric heating system

These technologies represent the dominant zero emissions heating technologies (at the point of use) being used by developers that emerged in the stakeholder interviews and literature review. All buildings represented in the scenarios are assumed to have been built to meet the minimum standards set out in the 2019 Scottish building standards[16]. It should be noted that there were additional zero emissions heating technologies being explored and considered by stakeholder interviewees, but these had not yet entered into mainstream use and were still at the piloting or design consideration stages.

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[15] Ambient loop heat networks have not been considered within the study due to the difficulty in finding reliable benchmark data for this fast emerging district heating technology option. However, it should be noted that ambient loop heat networks have the potential to provide a viable technology solution for new build developments and should be considered in project technology appraisals where possible.

[16] https://www.gov.scot/publications/building-standards-technical-handbook-2019-domestic/6-energy/6-2-building-insulation-envelope/

Table 1: Scenarios for cost analysis - detailed description

Scenario name	***Description***	***Geographical location***	***Development assumption***	***Assumed commercial delivery model for the development***
1. Private housing development	Collection of 300 3-, 4- and 5-bedroom detached and semi-detached homes with medium-sized front and back gardens, along with driveways and garages. The development includes 25% affordable homes.	Sub-urban development on the edge of a medium-sized City (e.g. Perth)	Semi-detached Home (3 bedroom) – 90 units Semi-detached Home (4 bedroom) – 30 units Detached Home (3 bedroom) – 90 units Detached Home (4 bedroom) – 30 units Detached Home (5 bedroom) – 60 units	Build to sell – Maximise profit from house sale (minimise capital costs of building the development)
2. Mixed-use, urban development	20 multi-storey buildings forming space for commercial shops, cafes, restaurants on the ground floors, alongside offices and apartments containing 1- and 2-bedrooms on the upper floors. The development is taking place on a previously disused site in a central area of a central-belt Scottish city.	Central-belt City (e.g. Edinburgh)	Apartments (1 bedroom) – 50 units Apartments (2 bedrooms) – 200 units Apartments (3 bedrooms) – 150 units Office space (5000 m^2) – 2 units Retail space (500 m^2) – 3 units Food shop (e.g. café) (500 m^2) – 2 units	Build-to-rent – Partnership model with third party energy supplier for zero emissions heat supply provision
3. Social housing development	Mix of 30 semi-detached houses (3, 4 and 5-bedroom) with small gardens, and 30 low-rise flats (1- and 2-bedroom, 3-storey) with communal gardens	Sub-urban development on the edge of a town (e.g. Cumbernauld)	Apartments (2 bedrooms) – 10 units Apartments (3 bedrooms) – 10 units Semi-detached Home (2 bedroom) – 10 units Semi-detached Home (3 bedroom) – 5 units Semi-detached Home (4 bedroom) – 5 units Detached Home (3 bedroom) – 3 units Detached Home (4 bedroom) – 4 units	Build-to-rent – tenant pays the energy bills for their home Looking to maximise the thermal comfort and minimise energy costs for tenants (wellbeing and affordability).
4. Small-scale rural development	Small development of 10 detached homes in a remote rural area, each with large private gardens, driveways and garages	Northern Rural / Island	Detached Home (2 bedroom) – 3 units Detached Home (3 bedroom) – 4 units Detached Home (4 bedroom) – 2 units Detached Home (5 bedroom) – 1 unit	Build to sell – Maximise profit from house sale (minimize capital costs of building the development)
5. Student accommodation	Single-room, en suite accommodation for 196 students spread over 6 floors, with a shared kitchen between every 8 rooms and large social space on every floor, retail offer on the ground floor and a café.	University city e.g. Aberdeen	A proxy is used for this scenario since appropriate benchmarks were not available for the building type and use. The scenario assumes: Apartments (3 bedrooms) – 111 units Which are intended to represent 6 single, en suite bedrooms, with on shared kitchen and access to communal spaces in the buildings, connected through corridors	Build, own, operate – full lifetime cost of the system is considered
6. Primary school	Primary school for 210 students	Semi-rural area e.g. Inverness	Primary school building covering 5,300m^2	Local school built as part of a house development, with specifications set by the local authority, who then go on to own and operate the site.

Assumptions and limitations of the cost analysis

Details of the model assumptions including fabric efficiency and resulting thermal demand, technology prices, electricity costs are included in Appendix 8: Database of benchmarks and assumptions used within the cost analysis.

It should be noted that the following cost dimensions have been excluded from the analysis:

- The capital costs of heating system pipe works within buildings have not been modelled for any of the technologies due to the complexities of assumptions that would be needed for these costs across different building types. However, this pipework cost would be largely the same for household level wet heating systems using either the baseline case of a traditional gas boiler system or zero emissions heating technologies (and differences in radiator size requirements for lower temperature heating systems are included in the model assumptions). Differences in internal building pipework costs could exist in multi-unit buildings using a centralised whole-building-level heating system or a district heating network connection but it was judged based upon real-world project experience that this would make up only a marginal proportion of the overall technology capital costs. Instead, a sensitivity analysis to the capital cost assumptions is applied in Section 6, which enables consideration of the impact of changes to this dimension of the cost for each technology.
- Fabric energy efficiency of the buildings was not the primary focus of this research, and as such a baseline assumption of fabric efficiency in line with current Scottish Building Regulations and established practice was made in in the cost analysis to enable thermal energy demand assumptions for different building uses and archetypes. As a result, the construction design and build costs for the buildings have not been included in the cost analysis, as the introduction of zero emissions heating technologies under these circumstances do not require significant changes to current practices. Nevertheless, this creates a limitation in the cost model's capabilities to consider the cost implications of increased fabric efficiency in buildings and the trade-off in terms of heat supply requirements. These limitations are discussed in more detail in Section 0, where the cost implications of Passivhaus-standard buildings are considered.
- Significantly, the costs associated with power network upgrades and grid connection costs for new builds are out of scope of this study. There is expected to be increased demands on the grid due to the electrification of heat and transport, which are likely to present short-term challenges due to capacity constraints of local electricity networks. Direct electric heating (and to a lesser extent electric heat pumps) will further heighten this impact, particularly due to the peak demands for heating (i.e. morning and night). This potentially significant cost to developers is considered in a parallel study, undertaken by Ricardo Energy & Environment on behalf of the Scottish Government (Ricardo Energy & Environment, 2020). Where stakeholders mentioned this issue within interviews for this study, their comments have been noted in the interview analysis and the potential implications for the output of this analysis are discussed.

4 Literature review

This literature review begins by presenting a summary of the zero emissions heating technologies considered in the cost analysis, including: technology definition; level of relevant literature on this area and any gaps; any key figures that are cited - noting any gaps in key figures; and, qualitative description of factors that affect the costs of the technology. More detailed findings from the literature review process can be found in appendices 2-7. Following this, we present an overview of less commonly featured technologies; the construction industry; non-domestic buildings; and scenarios and modelling.

More details regarding search terms and literature review methodology can be found in Appendix 1. All articles and reports reviewed herein are listed in Section 0 (8 References).

Table 2: Summary of key findings from the literature review relevant to costs of Zero Emissions Heating Technologies. More details on each technology are included In Appendix 2 to Appendix 5.

Technology definition / scope	***Level of relevant literature on this area and any gaps***	***Any key figures that are quoted/cited - noting any gaps in key figures***	***Qualitative description of factors that affect the costs of the technology***
Air source heat pumps (ASHP) - ASHPs work by mechanically moving heat from a cold location to a hotter one. - Air to air heat pumps can meet space but not water heating requirements. - Air to water heat pumps can meet both space and water requirements. - In the cases of both technologies, costs will depend on the size and energy efficiency of the target property which will determine sizing and system requirements.	- Abundant literature concerning *air to water* heat pumps including: CAPEX, new build cost reductions, future cost reductions, consumer perceptions, housebuilder perceptions, and factors that affect cost. - Less literature concerning *air to air* heat pumps; however, CAPEX is featured in at least one report. - Significant gaps re both technologies include OPEX and REPEX costs.	- Air-to-water heat pump CAPEX ranges from £5,000 to £21,550 (for unit sizes ranging from approx. 4kW to 16kW). - Lack of hard figures re OPEX and REPEX. - Costs reductions reported as 10% lower for new build vs retrofit. - Future cost reduction potential estimated at around 20% (largely non-equipment costs). - Air-to-air heat pump CAPEX ranges from £1,500 to £8,800 (for multiple 2kW units used to heat 1 – 4 bedroom apartments) - Lack of hard figures on OPEX and REPEX.	- Electricity prices. - Energy efficiency of property and heat demand. - Subsequent sizing of the heat pump system. - Auxiliary heat supply. - Existing capacity of low voltage local networks (if installed at scale). - Sub-optimal supply chain including lack of installer skills and experience leading to increased installation costs.
Ground source heat pumps (GSHP) - GSHPs work by mechanically moving heat from a cold location to a hotter one. - GSHPs can meet both space and water requirements. - System requirements are determined by the size and energy efficiency of the target property.	- Abundant literature concerning GSHPs including: CAPEX, new build cost reductions, future cost reductions, consumer perceptions, and factors that affect cost. - Significant gaps include OPEX and REPEX costs.	- CAPEX ranges from £8,000 to £27,350 (for unit sizes of 8kW to 12kW). - Lack of hard figures re OPEX and REPEX. - Costs reported as 10% lower for new build vs retrofit. - Future cost reduction potential estimated at around 18% (largely non-equipment costs).	- Geological specificities of site (if borehole drilling is required). - Electricity prices. - Energy efficiency of property and heat demand. - Subsequent sizing of system. - Existing capacity of low voltage local networks (if installed at scale)
Water source heat pumps (WSHPs) - WSHPs can meet both space and water requirements.	- Lack of literature concerning WSHPs. Referred to as a heat input source for 5th Generation District Heating and Cooling. - Significant gaps include CAPEX, OPEX, REPEX, new build cost	- Lack of hard figures re CAPEX. - Lack of hard figures re OPEX and REPEX.	Lack of evidence

- System requirements are determined by the size and energy efficiency of the target property.	reductions, future cost reductions, housebuilder perceptions, and factors that affect cost.		
Heat networks/ district heating cooling - Heat networks work by generating heat at a centralised location and transporting it through a network of pipes to end-users. - Heat networks are frequently cited in the existing literature as a decarbonisation of heat option, considered as both a retrofit and new build solution (when there is high enough demand e.g. non-domestic). - Heat networks can meet both space and water requirements.	- Abundant literature concerning HNs including: CAPEX, OPEX, future cost reductions, public perceptions, and factors that affect cost. - Significant gaps include: REPEX costs and potential cost reductions re new build versus retrofit.	- CAPEX ranges from £351,705 (£/MWth) for a biomass boiler to £2,400,000 (£/MWth) for a sewage source heat pump ○ Uncertainty around the cost of large, bespoke (MW-scale) heat pump systems as input source - OPEX ranges from £2,625 (£/MWth) for an Industrial Waste Heat Pump to £12,000 (£/MWth) for a sewage source heat pump - Lack of hard figures on REPEX	- Capital and operational costs highly dependent on heat source input. - Diameter of pipes, storage requirements, heat interface units, and emitters all impact upon capital and operational costs. - Other factors include: options for co-generation; climate; selection of a furnace/burner; heat exchanger selection; power failures; electricity prices; and, socio-political context (including policy environment) - Price reductions expected over time but highly variable and dependent upon a multiplicity of factors and potential scenarios (see Appendix 5 for more details).
Zero carbon buildings (ZCB)/ zero carbon homes (ZCH) - Zero carbon homes as consisting of one or a mix of: (1) good fabric energy efficiency, (2) onsite low/zero carbon heat and power technologies, or (3) allowable solutions to compensate carbon emission reductions. - ZCBs and ZCHs are frequently cited in existing literature as a no regret decarbonisation option when considering new builds. - In the context of Scotland and the UK, Passivhaus is the most frequently cited standard.	- Abundant literature concerning ZCB/ZCH including: CAPEX, future cost reductions, construction industry perceptions, and factors that affect cost. - Significant gaps include hard figures for OPEX and REPEX,	- CAPEX quoted at £1,465/m^2 or 15% extra investment - Lack of hard figures re OPEX and REPEX. - Lack of hard figures re scope for future cost reductions however literature suggests that the economies of scale available in the commercial housebuilding model would be equally applicable to mass construction of ZCBs and ZCHs (provided that became the norm). - See Appendix 6 for breakdown of elemental costs for Passivhaus standard.	- Reports of little correlation between dwelling energy demand and the appropriateness and scale of Low and Zero Emissions Generating Technologies. - Insufficient volume from any single source (commissioning body) to drive a standard design or a standard approach. - The geographic spread of projects across the country has not exposed the supply chain to the practice required, so there is very limited skills-building, experience or learning being generated. - Reports of performance gaps, however, there is conflicting evidence on this matter in the existing literature.

4.1 Less commonly featured technologies

Less commonly featured technologies in the existing literature on low carbon heating included: hybrid heat pumps; biomass; and, individual energy efficiency measures.

Hybrid heat pumps have not been considered in this review as per the scope of the proposed zero emissions buildings standards that heating systems should be zero emissions at the point of use. Biomass systems are also out of scope for this study. However, a brief review is presented below as to share initial evidence gathered at the early stage of the project before technology scope was specified.

Individual energy efficiency measures are usually included as part of Passivhaus (or other zero carbon homes) standards. A couple of reports and articles (namely Passivhaus Institut, 2012; Berry & Davidson, 2015) provide a breakdown of elemental costs but this seems to be the exception rather than the rule (see Appendix 6 for details).

4.2 Construction industry

- Similar to other parts of the United Kingdom, the Scottish housing system is characterised by a dependence on mainstream volume builders who are reluctant to depart from standard house types (UK Collaborative Centre for Housing Evidence, 2019).
- Whilst drivers for zero carbon home building exist in the UK, the barriers are currently perceived to be greater than the drivers (Heffernan et al., 2015; Osmani and O'Reilly, 2009).
- Drivers include: legislative, economic, social responsibility, individual, cultural and industry (Heffernan et al., 2015; Osmani and O'Reilly, 2009). See Appendix 7 for more details.
- Barriers include: economic, skills and knowledge, industry, legislative, design and cultural (Heffernan et al., 2015; Osmani and O'Reilly, 2009). See Appendix 8 for more details.

With specific regard to house builders' perspectives of heat pumps (as opposed to zero or near zero carbon home building more broadly), according to the Committee on Climate Change (2013):

> *'After being provided with information and asked how they [members of the construction industry) feel about different heating appliance options, 40% said they felt very or fairly negative about air source heat pumps, compared to 29% that felt positively. Ground source fared a little better, with 30% feeling very or fairly negative and 38% feeling fairly or very positive. The reasons given for attitudes toward air source systems included concerns about noise, the visual appearance of the external unit, concerns about vulnerability of the external unit to tampering and scepticism that the system would provide sufficient heat on cold days.'*

This suggests a lack of knowledge about zero emissions heating technologies in the construction industry (although it should be noted that this study is now a relatively old piece of research). This has the potential to add costs to constructing new build homes due to uncertainty and additional time needed to deviate from the established modular approaches to delivering homes.

- With regards to business models, there are some articles in the international literature which explore case studies of innovative business models and commercial delivery strategies to realise ZCBs. To summarise, business as usual is failing to deliver ZCBs; innovation on behalf of developers and other stakeholders is likely to be required if the socio-political context does not change (Pan & Pan 2020; Zhao & Pan, 2015; Zhao, Hwang, & Lu, 2018).

4.3 Non-domestic buildings

The majority of the existing literature focusses on domestic as opposed to non-domestic buildings. However, it should be noted that although this review considered both domestic and non-domestic new builds, greater focus was placed on domestic new-build literature since there was insufficient time in this study to search for literature on the diverse range of non-domestic building archetypes that exist. This was reflected in the search terms and subsequent report and articles reviewed (see Appendices 1 and 2). It is therefore expected that a more significant body of literature does exist for non-domestic buildings.

- Depending on end-use, it is possible that there may be fewer barriers to realising zero carbon buildings in non-domestic settings than for domestic counterparts. For example, scholars have reported that civic rented zero carbon buildings (ZCB) are more readily accepted by end-users as well as being more readily accessible to those with limited capital who can use ZCBs and devices without paying the entire associated costs of CAPEX, OPEX and REPEX (Zhao, Hwang & Lu, 2018). However, despite some research which suggests that high-performance non-domestic buildings (such as offices for example) can be built cost competitively compared to more traditional building designs (e.g. Pless & Torcellini, 2012), this review has found little evidence to suggest that this is the case re the non-domestic building sector in Scotland or the UK more broadly.

4.4 Scenarios and modelling

Scenarios and modelling are frequently observed in the existing literature (especially the UK grey literature).

- This includes: Maclean et al. (2016): Managing Heat System Decarbonisation. Comparing the impacts and costs of transitions in heat infrastructure; BEIS (2019): Alternative Heat Solutions: Converting a Town to Low Carbon Heating; National Infrastructure Commission (2018): Cost analysis of future heat infrastructure options; Carbon Trust (2018): Estimating the cost-reduction impact of the Heat Network Investment Project on future heat networks; UK Gov (2016): Heat Pumps in District Heating; Niskanen and Rohracher (2020): Passive houses as affiliative objects: Investment calculations, energy modelling, and collaboration strategies of Swedish housing companies; Cozzini, M. et al. (2018) District heating and cooling networks based on decentralized heat pumps.

The scenarios, modelling procedures, and assumptions used to inform analysis are in many cases diverse, detailed and intricate. To provide an example, Maclean et al. (2016) used four simplified housing typologies (urban, suburban, rural, flats) whereby:

> *'for each combination of network solution and housing type, a comparison between the existing natural gas solution is made and impact assessed using quantitative and qualitative analysis of a series of cost (based on current levels) and impact criteria including: efficiency of heat production; gas/electricity/fuel price; delivered heat cost; production and supply issues (including sensitivity for Carbon Capture and Storage*

> *and energy storage); cost per household of new and reinforced infrastructure; property conversion rates; trench size for cables and pipes; access and traffic disruption; requirement for structural improvement/energy efficiency; requirement for new/modified appliances; cost per household to convert; disruption; customer acceptance; regulation issues'*

Although this literature review does not present the specifics of how scenarios and modelling have been used to explore the costs of scale-up regarding various zero emissions heating technologies, data has been gathered throughout this process to feed into the relevant work packages within the wider research project.

5 Stakeholder interviews

The findings presented in this section represent an analysis of ten semi-structured interviews with key stakeholders representing both new build developers and low carbon technology supply chain actors. The findings from this analysis were used to supplement and refine the findings of the literature review to inform the development of the scenario cost model.

5.1 Commercial delivery models and choice of zero/low emissions heating solution

Table *3* summarises key themes from the interview analysis regarding the commercial delivery models used by the different types of actors and key considerations in choice of zero / low emissions heating solution. This delivery model was fundamental to the type of technology choices that were preferred for each type of development, reflecting how each technology option results in a different split of the costs between CAPEX, OPEX and REPEX over their lifetime. However, choices of low / zero emissions heating technology were influenced by more than cost factors, including the space required for a certain technology, control responsiveness, occupant familiarity and preference, and model of operation and maintenance.

Table 3: Commercial delivery models used by the different types of actors and key considerations in choice of zero / low emissions heating solution

Type of actor	**Description of commercial delivery model**	**Factors that influence choice of zero emissions heating technology (including cost)**
Student accommodation	Build, own, operate – full lifetime cost of the system is considered	- Space maximisation for student accommodation (i.e. technologies without large plant rooms are preferred) - Performance control (responding quickly to occupancy patterns, thermal comfort, minimising overheating) - Capital cost minimisation (e.g. reducing costs by using direct electric heating rather than a wet heating system) - Embodied carbon – direct electric was considered to have less embodied carbon than a wet system - Policy requirements on new build imposed by local authority and national building standards - The large scale of many student accommodation providers meant that preferential electricity tariffs could be negotiated.
Mixed-use development	Build-to-rent, – full lifetime cost of the system is considered - Using a partnership model with third party energy supplier for district heat supply option - “*where each stakeholder manages the risks best suited to them*”	A large multi-use development in a dense city centre area was seen as a candidate for a heat network, particularly with the potential to make additional connections to neighbouring buildings over time and local renewable heat sources. The costs of such a network are influenced by factors including: - Business rates on the heat network option - Future (potential) expansion of the network to surrounding area - Balance of heating and cooling demand - Nearby sources of ‘waste’ or surplus heat (e.g. sewer system / data centre etc.)
Private housing development	Build to sell – maximise profit from house sale (minimise capital costs of the development) - House designs can be developed at a UK-level and adapted and applied across multiple sites - 25% of all developments are made up of affordable housing and sold on to	- Building standards and the associated SAP calculations tool are the key driver of technology decisions, with the SAP tool used to calculate options for compliance and compare costs. House builders were keen to have access to the next release of the tool in advance of new regulations coming in - Range of technologies considered to meet zero emissions heating target: ASHPs (began with gas hybrid ASHPs), exploring the potential of other technology options include infrared heat mats - GSHPs were not considered suitable due to lack of space for ‘Slinkies’ (heat collectors, horizontal array), and complicated ownership model of shared boreholes.

	a housing association / local authority.	- Solar PV was not required to meet required SAP rating going forward. - Potential for land developers to offer district heating as part of their fully-serviced land offer, particularly where electricity grid is constrained. - Potential grid upgrade and connection costs were a significant concern (electric vehicles were also noted as a critical influence on the required electricity demand and costs); - Potential for price reductions through bulk buying deals for larger developers (although these are often done at a UK level and unlikely to have been agreed in time for Scottish 2024 standards) - Bronze / Silver / Gold planning rating for developments were a potential influence over technology choice where planning permission was competitive (GSHPs resulted in a higher rating than ASHPs)
Social housing development	Build to rent – tenant pays the energy bills for their home Looking to maximise the thermal comfort and minimise energy costs for tenants (wellbeing and affordability). *“we are there to provide a service to people who are not well off. […] If it costs an extra £10,000 a house to do it, but if the outcome is that the tenant has an affordable, comfortable home then that’s the right thing to do.”* (Housing association interviewee)	- Examples of strong innovation driven by the technical specialists within the housing associations: o Exploring optimum levels of fabric efficiency, use of thermal and electric storage, energy as a service (energy with rent), smart energy networks. o Use of concrete mass of the floor with underfloor heating as a thermal store o Use of dynamic electricity tariffs / variable tariffs and heat storage to minimise heat costs - Lifetime technology costs are a key metric - Target of 30-year timescale to pay back loans for new builds. - Tenant preferences: One interviewee reported that tenants preferred modern storage heaters to ASHPs due to ability to control them - Considerations in rural locations: o Maintenance requirements and the emissions associated with travel to carry out regular maintenance. ASHPs required annual maintenance whereas direct electric heating did not. o More extreme weather conditions require higher fabric efficiency combined with mechanical ventilation

5.2 Other factors affecting technology choice and costs

Power grid upgrade costs

A barrier experienced by a range of the stakeholders interviewed was the constrained power grid, requiring the building of additional capacity to support proposed new developments.

> *"It's not necessarily the costs of the [heating] technology, but more the associated infrastructure costs for electrical heat"* (house builder interviewee)

Grid upgrade costs created a significant challenge to the commercial viability of developments and in the case of smaller developments made them unviable, according to interviewees. Larger scale, phased developments were having to change and upgrade their power infrastructure investment plans mid-process to allow for the additional electricity demand that had not been factored in at the start of the design process. There was a recognition across the stakeholders interviewed that smart grid approaches and use of various forms of storage were likely to be critical to enabling the viability of developments going forward, although examples of applying these solutions in developments was only evident in the social housing sector.

This issue is not reflected in the cost analysis presented in this study, but the implications of these costs are explored in detail in a parallel study conducted for the Scottish Government (Ricardo Energy & Environment, due for publication 2021).

Supply chain, skills and quality

There was recognition amongst stakeholders that delivering zero emissions heating solutions in new build was a relatively new dimension of work for many new build developers and the supply chains that support them.

> *"We recognise this is **a transformational period for** the direction we're going in. 2024 is the date in Scotland, and it's going to be challenging, but our experience of Covid has taught us that when it comes to the crunch we all collaborate and we can achieve this."* (House builder interviewee)

There was some experience of increased costs to low / zero emissions developments due to uncertainty and inexperience of supply chain contractors delivering the works charging inflated rates to cover risks of errors.

Developers themselves also had differing levels of knowledge and experience held in-house. For example, where housing associations took responsibility for their own house building, there were project managers embedded in the organisation who held expertise and experience to inform the fabric efficiency and heating system specification. This led to design optimisations and experimentation with new technology options. Although there was early evidence of some established dominance of ASHPs in the domestic sector, the zero emissions heating market was still a developing market with practice not yet established within the dominant players in the market.

Adaptation of commercial delivery models

Private sector new build developers had established delivery models, predominantly based around the use of gas boilers for heating, which enabled efficient delivery and cost savings throughout the process. The zero emissions heating technologies considered in this study did not all fit easily within these established delivery processes, set up around a building-level heating solution that can be passed over from developer to building owner to take responsibility for operation, maintenance and replacement. This posed barriers to technologies that required alternative set-ups such as district / communal heating systems that required some form of joint-ownership set-up and / or third party operator for the duration of the system's lifetime. There was little evidence from the interviews that these solutions were yet under consideration in the private housing development sector, despite these technologies having greater cost and energy efficiency benefits in certain circumstances. This suggests that there is potential for development of new delivery models or energy service companies to enable use of the most efficient zero emissions heat solution (i.e. ambient loops / heat networks) that won't necessarily be used if housing / land developers have to deliver heat as a service themselves.

The next section presents a cost analysis for the six scenarios and technology options defined for the study, including a sensitivity analysis on key variables to understand the cost impact of the technology design decisions and influences described in the previous sections.

6 Scenario analyses

The following section presents the cost analysis results for the study's six scenarios (a brief summary of each scenario is set out below).

First, the results for different cost dimensions associated with each technology are presented in detail for scenario 1: the private housing development. Following this, a comparison is presented of the levelised cost results for all six scenarios, presenting an opportunity to discuss the impact of different developments on the resulting costs of delivering zero emissions heating. Finally, a sensitivity analysis is applied to three key assumptions within the cost model and scenarios to explore how changes in these key elements affect the overall cost of the technology solutions.

It should be noted that the costs of power network grid upgrades have not been included in any of the analyses (see study by Ricardo Energy & Environment, due for publication 2021) for more details on the potential scale of these costs). If these costs were represented in the analysis this would likely increase the Capex costs of the wet electric and dry electric heating options. The impact of grid upgrade costs is a key gap in this analysis that should be considered in future research

Scenario name	Description
1. Private housing development	Semi-detached Home (3 bedroom) – 90 units Semi-detached Home (4 bedroom) – 30 units Detached Home (3 bedroom) – 90 units Detached Home (4 bedroom) – 30 units Detached Home (5 bedroom) – 60 units
2. Mixed-use, urban development	Apartments (1 bedroom) – 50 units Apartments (2 bedrooms) – 200 units Apartments (3 bedrooms) – 150 units Office space (5000 m^2) – 2 units Retail space (500 m^2) – 3 units Food shop (e.g. café) (500 m^2) – 2 units
3. Social housing development	Apartments (2 bedrooms) – 10 units Apartments (3 bedrooms) – 10 units Semi-detached Home (2 bedroom) – 10 units Semi-detached Home (3 bedroom) – 5 units Semi-detached Home (4 bedroom) – 5 units Detached Home (3 bedroom) – 3 units Detached Home (4 bedroom) – 4 units
4. Small-scale rural development	Detached Home (2 bedroom) – 3 units Detached Home (3 bedroom) – 4 units Detached Home (4 bedroom) – 2 units Detached Home (5 bedroom) – 1 unit
5. Student accommodation	A proxy is used for this scenario since appropriate benchmarks were not available for the building type and use. The scenario assumes: Apartments (3 bedrooms) – 111 units Which are intended to represent 6 single, en suite bedrooms, with on shared kitchen and access to communal spaces in the buildings, connected through corridors
6. Primary school	Primary school building covering 5,300m^2

assessing the cost impacts of a shift to zero emissions heating in new builds.

6.1 Overall cost increases implied by the transition to zero emissions heating in new builds

The costs of the five zero emissions heating technology options all represented an increase in levelised lifetime costs compared to a counterfactual of a gas boiler supplied by the gas grid. Figure 3 shows how these lifetime costs range from 125%-331% of the costs of an equivalent gas heating system across the six scenarios and zero emissions heating technology options (where 100% represents parity with a gas boiler heating system).

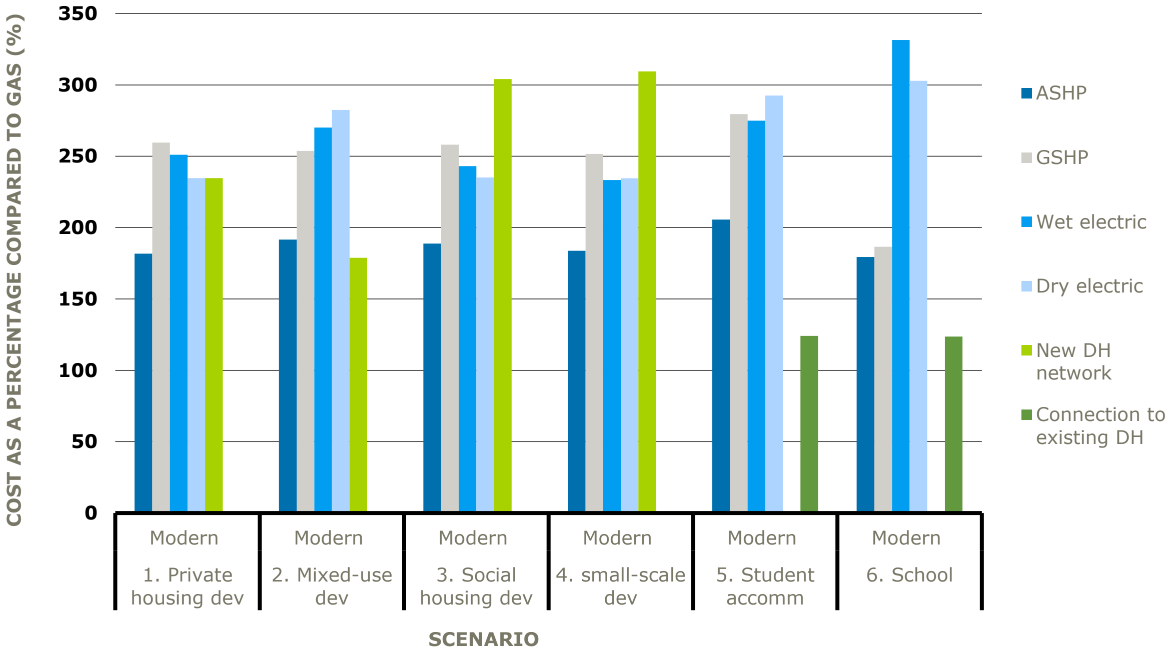

Figure 3: Percentage comparison of each technology's lifetime levelised cost for each new build development scenario against the cost of an equivalent gas heating system (note: Scenarios 5 and 6 consider the cost of connection to an existing heat network rather than development of a new system).

The following sections will explore in more detail how the costs for each technology are affected by the different contexts and development characteristics, as well as how these costs are split between the developer and building-user for different developer business models.

6.2 Scenario 1 in-depth analysis - private housing development

In Scenario 1, (the private housing development of 300 detached and semi-detached homes), a comparison of the levelised lifetime costs of five technology options finds that ASHPs are the lowest cost zero emissions heating solution for this scenario[17] (Figure 4).

*Note: costs displayed are for the development as a whole, rather than per house.

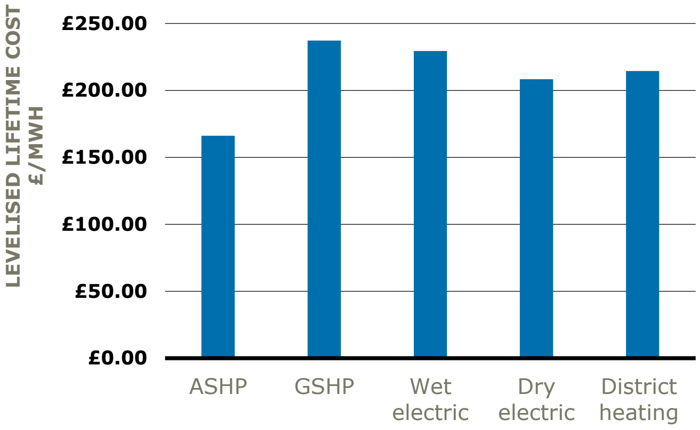

Figure 4: Levelised lifetime cost of each technology option for Scenario 1: Private housing development

The elements of the levelised cost; CAPEX, annual electricity costs, maintenance costs, and REPEX costs, are shown in Figure 5.

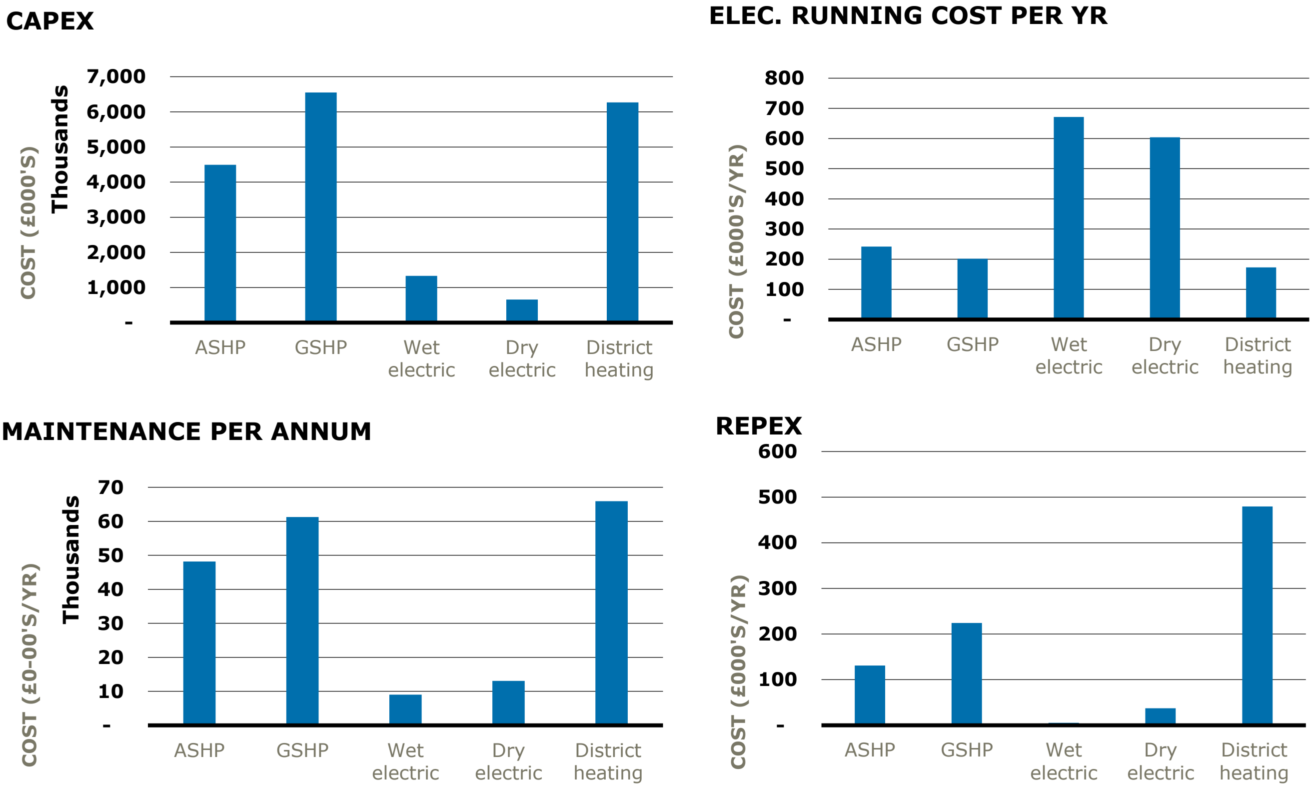

Figure 5: Scenario 1: Private housing development - Comparison of CAPEX. Fuel Cost (per year), Maintenance (per year) and REPEX of each technology option

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[17] The levelised lifetime cost is calculated using the undiscounted whole lifetime cost of a technology (including Capex, electricity costs, maintenance costs and replacement costs over a 40 year lifetime) divided by the total energy demand for the scenario over the lifetime (£/kWh). The lifetime considered for all scenarios is for 40 years.

For a private house builder seeking to build the homes to sell on once construction is complete, the CAPEX costs are likely to be the primary consideration. As shown in Figure 5, when considering the CAPEX costs alone, the direct electric heating options are significantly lower cost than the alternatives (although in practice interviewees did not consider these technologies compatible with the SAP rating required through current building standards).

When considering the electricity running costs of each technology, air-source and ground-source heat pumps are cheaper to run than the wet electric and dry electric systems due to their higher operational efficiency[18] (see 'Electricity Costs per Annum' Figure 5). It should be noted that the electricity costs per annum presented for district heating only include the required electricity to generate the heat demand for the assumed scenario, rather than the heat price charged to the end consumer, which typically includes multiple elements of the costs associated with district heating including the cost of heat generation, system repair and maintenance, metering and billing.

The distribution between developer costs and home-owner costs are illustrated in Figure 6, which compares the costs met by the house developer (CAPEX) against those met by the home owner (Electricity costs for Operation, Maintenance , Replacement). In this scenario, ASHPs appear to make the most favourable trade-off between customer and developer costs[19]. As would be expected, when solar PV is added onto the development, this has a further saving for homeowners' costs, but adds to the developers' capital costs.

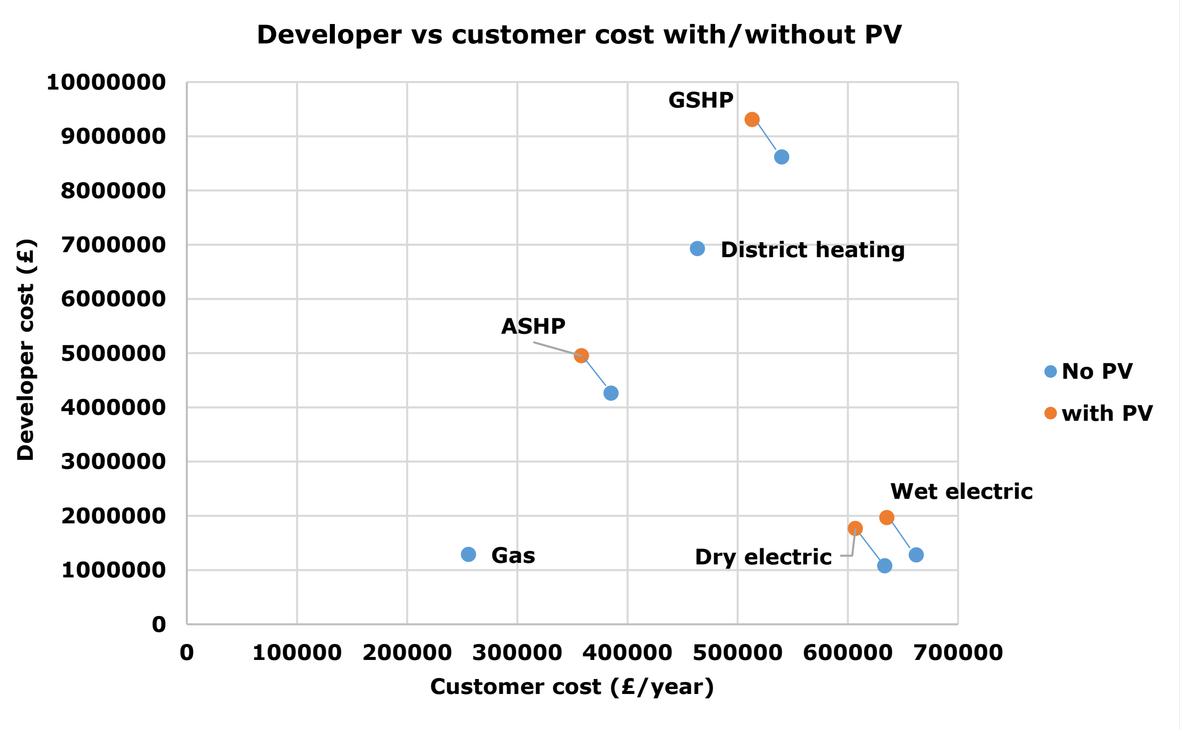

Figure 6: Scenario 1 Private housing development cost analysis: Comparison of the costs met by the house developer (CAPEX) and those met by the homeowner (Electricity costs for operation, Maintenance, Replacement)

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[18] Assumed coefficient of performance of ASHPs = 2.5 and GSHPs = 3.5

[19] Note: the 'cost to the customer' for district heating is not an accurate representation of how heat price would necessarily be calculated for such a heat network. However, the information is included for completeness of analysis.

The breakdown of results for all six scenarios are presented in Appendix 9: Detailed scenario results'. Next in this section we go on to compare the findings across the scenarios to understand the key cost elements and their impact on developer vs building owner/occupier.

6.3 Cross scenario comparison: Levelised lifetime cost

The levelised lifetime costs of each technology are compared across the six scenarios in Figure 7. The following assumptions should be noted:

- For Scenario 5 (student accommodation) and Scenario 6 (primary school), it is assumed that there is an existing district heating network that the building can connect to. The costs represented in Figure 7 for these scenarios are made up of pipework required to connect the building to an existing network, a substation to connect the building heating system to the incoming district heating supply and control units.
- The CAPEX costs of GSHPs could vary considerably depending on the ground conditions and set up of the system. This analysis assumes a vertical borehole (approx. 100-200m deep) with an average geology and ground composition delivering heat of 10-20°C. The impacts of a variation in the capital costs of a GSHP are explored in the following section on sensitivity analysis.

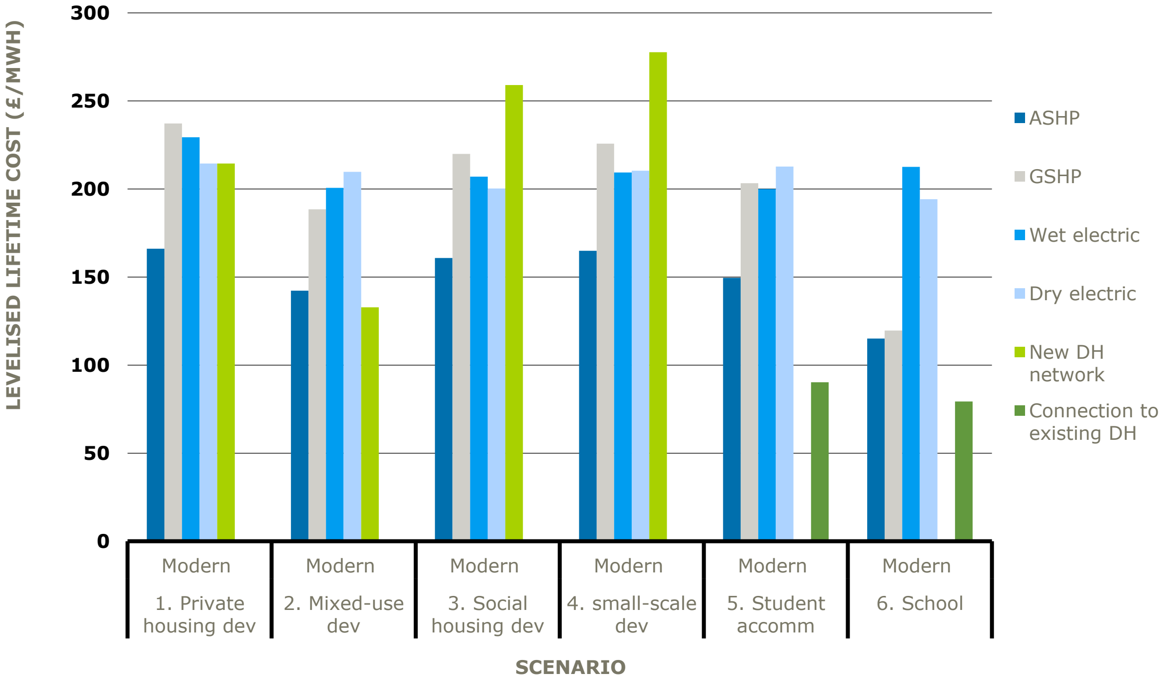

Figure 7: Comparison of the lifetime levelised cost (£/MWh) of each technology option across the six scenarios considered in the study

There is significant variation in the levelised lifetime costs of each technology across the scenarios, despite the lifetime costs having been levelised to enable comparison across the different scales of development. Some reasons for this include:

- The sizing of heat supply technologies to meet the heat demand profiles of each building archetype is only available in set generation capacities, with fixed costs attached to them.

- The fixed capital costs associated with district heating pipe infrastructure which do not vary in a linear way according to the size of a development. For example, developments with higher heat demand densities offset these infrastructure costs with operational efficiency gains and reduced peak supply requirements by spreading peak demands across the network.

In terms of individual building zero emissions heating solutions, ASHPs appear favourable from a lifetime cost perspective across all of the scenarios. Direct electric heating is likely to be more costly, and ultimately constrained, where there are existing capacity constraints on the local electricity network. It would be valuable to conduct further research to consider the cost implications of grid constraints on the scenarios. GSHP becomes more competitive for Scenario 6 (the primary school) where the heat demand profile provides a relatively constant load and thereby improved efficiency which can offset the higher capital costs of the GSHP. Finally, district heating becomes particularly attractive when a development can connect into an existing network, illustrated in scenarios 5 and 6.

6.4 Sensitivity analysis

There are a range of factors that might affect the results of the cost analysis conducted for each scenario. In this section we explore the implications of the following three factors in more detail:

(i) A variation in the CAPEX cost assumptions. For example, technology costs may reduce over time (due to technology innovations and supply chain growth) or increase (e.g. ground conditions may create additional costs for installing heat collectors for heat pumps; or local network electricity upgrades).
(ii) A variation in electricity prices.
(iii) The scale / design of a development may improve the cost-effectiveness of certain technology options.

Impact of a variation in CAPEX – example for Scenario 1: Private housing development

Figure *8* illustrates the potential impact on the levelised lifetime cost for the development of a variation (+/- 30%) in the CAPEX costs associated with each technology option. Clearly, technologies where capex is the largest proportion of whole life cost show the largest sensitivity to a variation in capital costs. In practice, there is the largest potential for variation in capital costs in newer technologies such as ASHPs and GSHPs, where technological innovation and growth in supply chains have the potential to drive down costs.

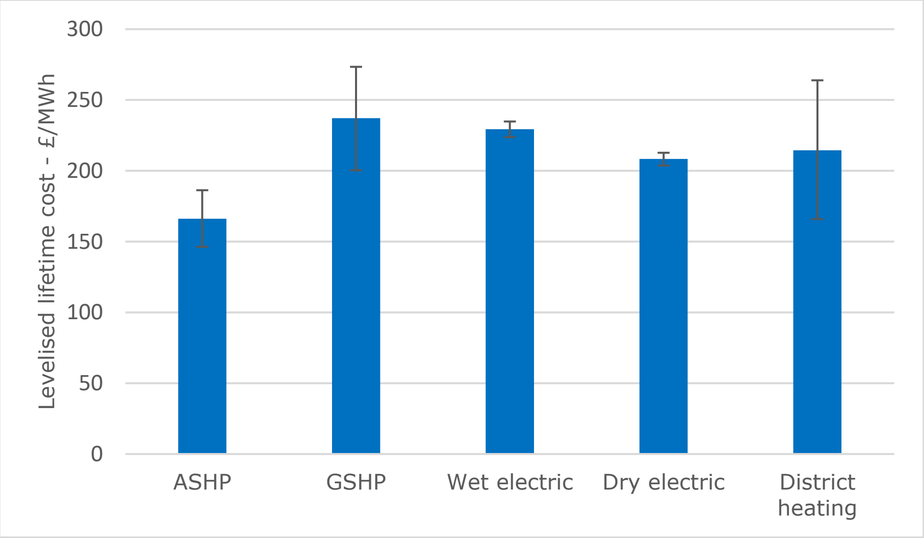

Figure 8: Levelised lifetime costs of heat for Scenario 1: Private housing development, with error bars illustrating the impact of a +/- 30% variation of the assumed CAPEX costs (£)

The assumed commercial delivery model for Scenario 1 involves the house builder constructing the home and then selling it on to customers; meaning that the CAPEX costs are a primary concern for their profit margins. Figure 9 shows the comparison of CAPEX costs for each technology with the sensitivity analysis applied. This suggests that even with significant reductions in the capital costs of GSHPs and district heating technologies of the form considered in this analysis (i.e. the technologies with the largest capital costs), they would still not compete from this basis with ASHPs or direct electric heating[20].

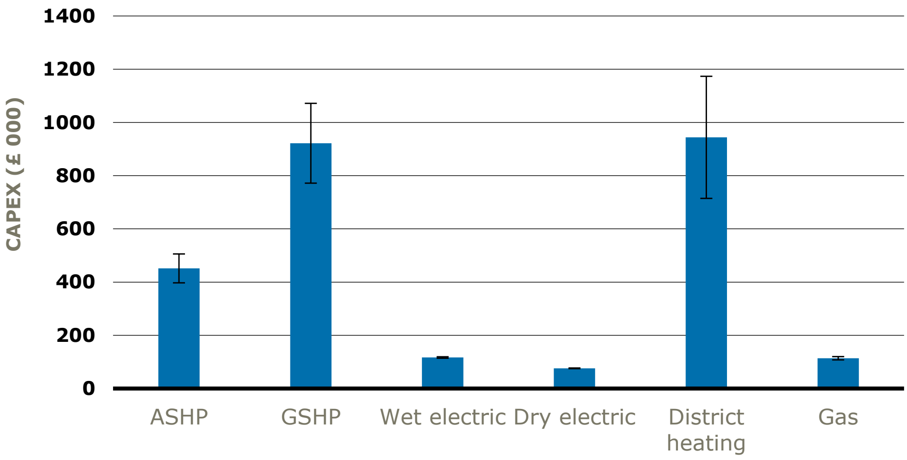

Figure 9: CAPEX costs for each technology applied to Scenario 1: Private Housing Development, with error bars illustrating the impact of a +/- 30% variation of the assumed CAPEX costs (£)

Of specific interest in the case of the immature supply chains of zero emissions heating technologies is the impact of a reduction of CAPEX. For example, the Committee on

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[20] There are technology variations that have not been considered within this scenario analysis that may produce different cost results. For example, shared ground loop arrays (a form of GSHP with a lower capital cost) or pre-existing DH networks have not been considered in this scenario analysis due to available data and time limitations. The findings presented should therefore only be viewed as an indication for a particular scenario, rather than a clear technology steer.

Climate Change Sixth Carbon Budget (2021) assumes a 20-30% reduction to 2030, 30-40% reduction to 2050 for HP unit and installation would be expected. The lower boundary of the sensitivity analysis presented here therefore represents the approximate capital costs for heat pumps for a point in time approximately between 2030 and 2050. Figure *10* presents the impact of a 30% reduction in CAPEX costs on the lifetime costs for each technology across the scenarios. The resulting lifetime costs range from 106%-328% of the costs of an equivalent gas heating system across the six scenarios and zero emissions heating technology options (where 100% represents parity with a gas boiler heating system).

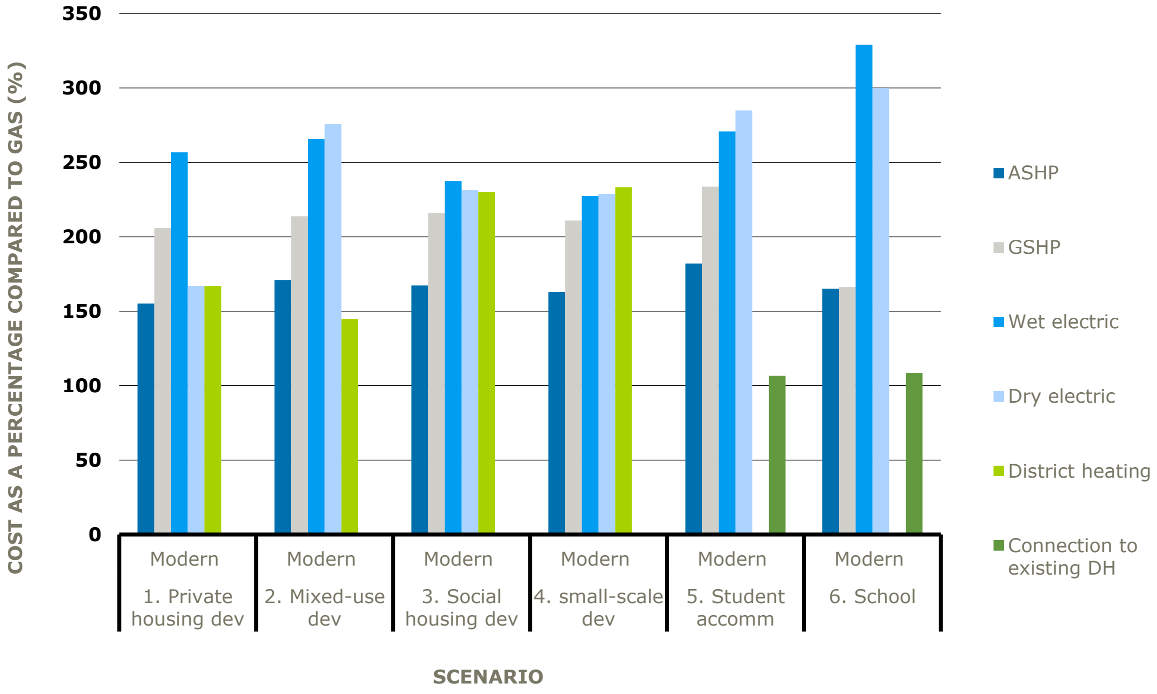

Figure 10: Percentage comparison of each technology's levelised lifetime cost for each new build development scenario against the cost of an equivalent gas heating system (note: Scenarios 5 and 6 consider the cost of connection to an existing heat network rather than development of a new network.

Impact of a variation in electricity running costs – example for Scenario 1: private housing development

Another key element contributing to the technology cost is the electricity running costs needed to meet heat demand. Figure *11* illustrates the potential impact on the levelised lifetime cost of a variation (+/- 30%) in the electricity costs associated with each technology option and Figure *12* presents the sensitivity of the electricity running costs in isolation. The figures demonstrate that an increase in electricity prices could lead to the wet and dry electric heating options becoming the most expensive technology options on both a lifetime cost basis and electricity costs basis. Given that a key decision criteria for profit-driven developers is minimising the capital costs of a project, this may result in technologies with the most expensive operation and maintenance costs being placed in new developments[21].

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[21] Note: The electricity running costs of district heating illustrated in the figure 11 are the direct electricity costs incurred to supply the Scenario's assumed heat demand. The heat price charged to the customer would likely be higher than this to cover maintenance and capital costs of the network.

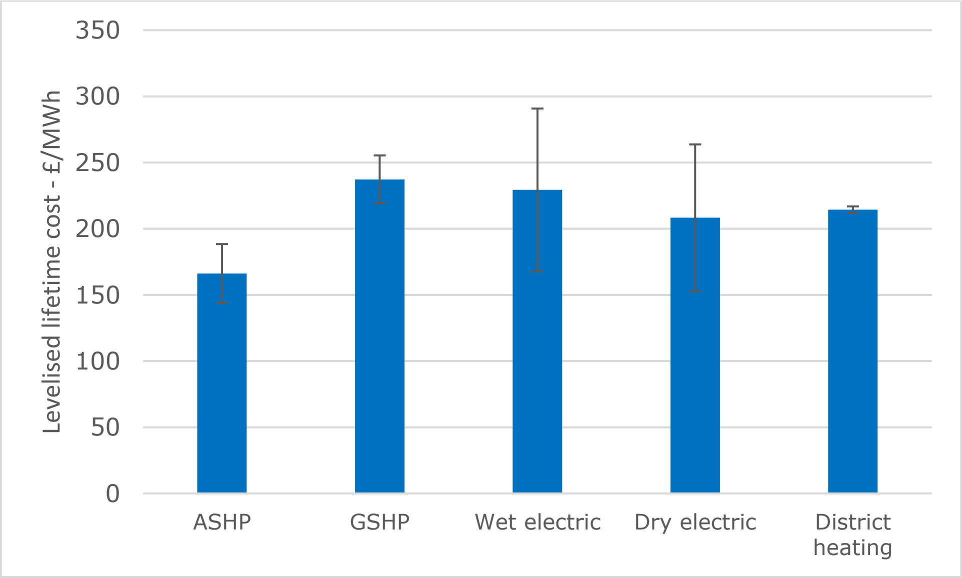


Figure 11: Levelised lifetime costs of heat for Scenario 1: Private housing development, with error bars illustrating the impact of a +/- 30% variation on the assumed electricity costs (£/year)

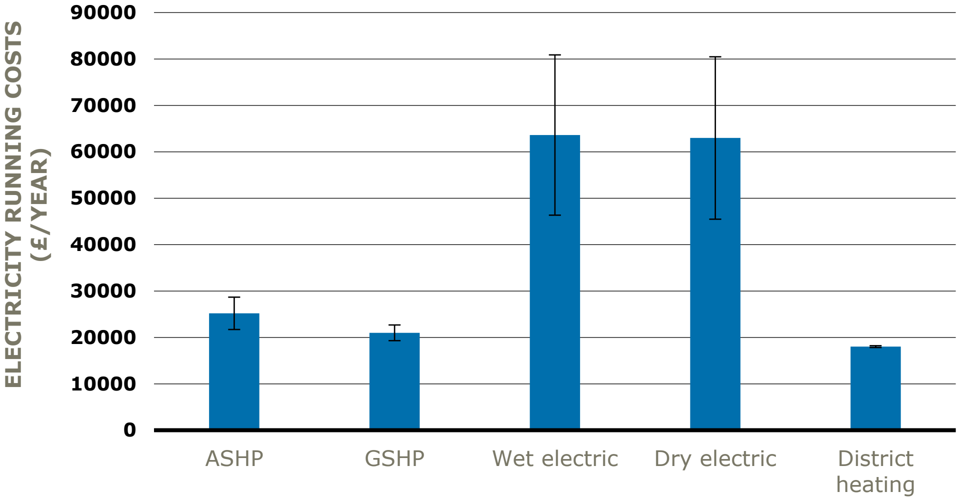


Figure 12: Electricity running costs (fuel cost) for Scenario 1: Private housing development, with error bars illustrating the impact of a +/- 30% variation on the assumed electricity costs (£/year)

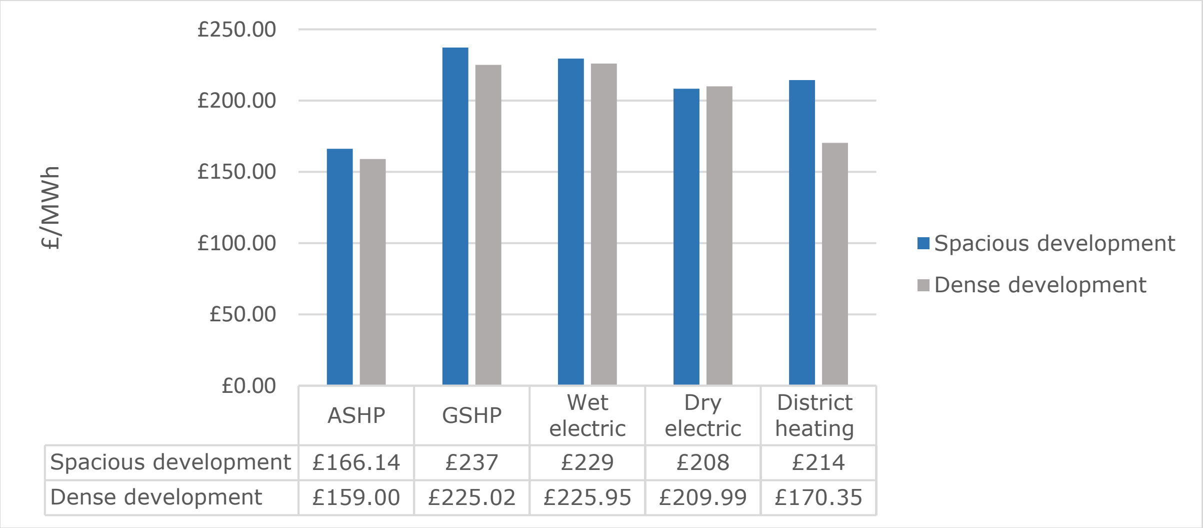
Impact of a variation in a development's heat demand density – example for Scenario 1: private housing development

This section considers the impact of altering the types of homes included in the 300 unit housing development represented in Scenario 1 to increase the heat density of the development. An example of such a development is defined in Table *4*, where the choice of home archetypes is shifted onto apartments, terraced homes and semi-detached homes (three and four bedrooms).

Table 4: Example of adjusted development assumptions for Scenario 1 (private housing development) to increase the heat demand density of the development

Scenario name	****Adjusted* development assumption***
1. Private housing development	Apartment (3 bedroom, built in blocks of 20 apartments) – 200 units Mid-terrace home (3 bedroom) – 48 units End-terrace home (3 bedroom) – 12 units Semi-detached Home (4 bedroom) – 40 units

Figure *13*: Comparison of the levelised lifetime costs (£/MWh) for each technology option in Scenario 1: Private housing development with the district heating costs for a more densely designed development. Figure *13* and Figure *14* Figure 5 present the results of this cost analysis for the levelised lifetime cost (£/MWh), and the CAPEX costs (£), comparing the results of the original development of semi-detached and detached homes to the denser development of apartments, terraced and semi-detached homes. ASHPs still appear the lowest cost option on a levelised lifetime cost basis, although by a smaller margin. When considering the CAPEX costs alone (the key metric for private developers seeking to minimise CAPEX for their development), district heating now has a significantly lower capital cost which is almost comparable to ASHPs.



	ASHP	GSHP	Wet electric	Dry electric	District heating
Spacious development	£166.14	£237	£229	£208	£214
Dense development	£159.00	£225.02	£225.95	£209.99	£170.35

Figure 13: Comparison of the levelised lifetime costs (£/MWh) for each technology option in Scenario 1: Private housing development with the district heating costs for a more densely designed development

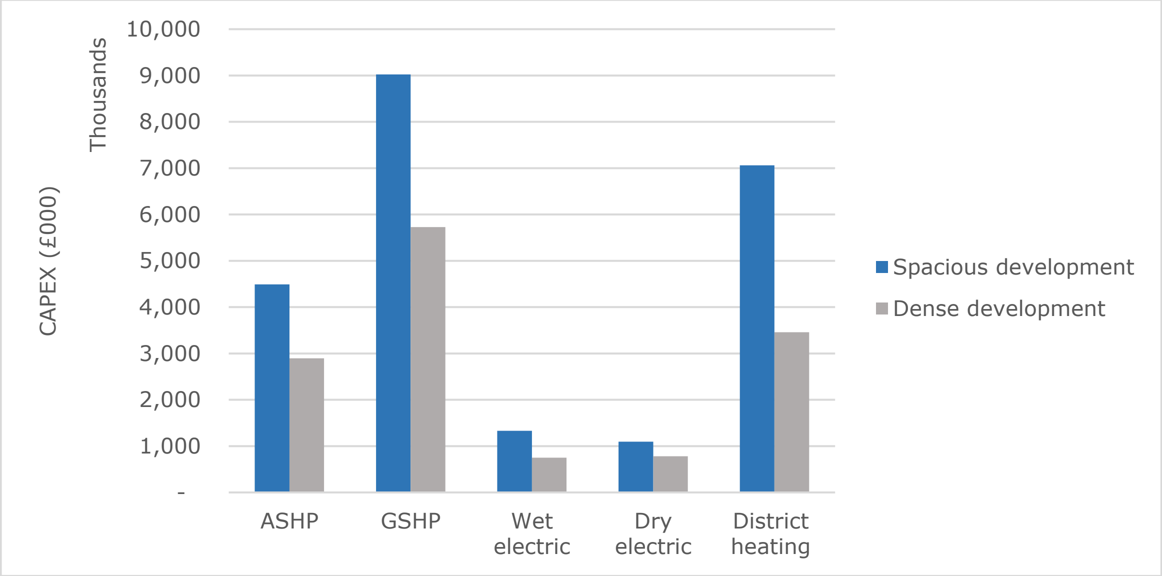


Figure 14: Comparison of the CAPEX costs (£) for each technology option in Scenario 1: Private housing development with the district heating costs for a more densely designed development

6.5 Considering the costs of meeting Passivhaus standards for Scenario 1: Private housing development

A key concern in the delivery of zero emissions heating is finding the optimum balance of building fabric efficiency vs. the supply of zero emissions heating. As discussed in the methodology, the primary focus of this study was on the costs of zero emissions heating supply technologies in new build developments, rather than on the costs of energy efficiency measures. The cost analysis model developed for the study assumed a baseline of energy efficiency which aligns with existing building standards[22] and current practice reported in stakeholder interviews. This section considers how the zero emissions heating costs would be affected if the homes developed in Scenario 1 (the private housing development of 300 homes) met Passivhaus standards, reaching a thermal energy demand of 15kWh/m^2/year.

The analysis presented here is an approximation of the costs of reaching Passivhaus standards in new builds, based upon assumptions that could be made within the constraints of the cost analysis model and the time constraints of the project. The following assumptions are made within the analysis:

- The CAPEX cost calculation only considers the *additional* design and construction costs of meeting Passivhaus standards compared to meeting the minimum standards set out in the 2019 Scottish building standards. This is assumed to be £119/m2, based upon data from Passivhaus Trust (2019). This cost excludes the costs of any heat recovery and heat supply technologies.
- Buildings are still assumed to need a small central heat source and emitters to meet space heating demands.
- No additional equipment (i.e. heat recovery systems which are required in practice) were included in the model
- The energy consumption behaviour of building occupants in the Passivhaus heating patterns/consumption remains the same as modern standards. The only

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[22] The baseline energy efficiency is assumed to be the minimum standards set out in 2019 Scottish building standards. Heat demand assumptions for buildings were based on refined industry benchmarks using information from metered data from previous Ramboll projects.

changes taken into account are a reduced peak heat demand, annual fuel consumption and reduced heating unit size vs increase in CAPEX using the above assumption
- Passivhaus consumption and peak data were calculated using information from Passivhaus Trust (2019), supported by benchmarks used by the Ramboll energy team
- District heating is not considered viable for the Passivhaus scenarios. This is because district heating systems benefit from high heat demand density to make the interconnecting infrastructure financially viable, whereas Passivhaus encourages low heat demand density.

Based on the high-level nature of these assumptions, the analysis presented below only represents an indicative comparison of the costs of different fabric efficiency and heat supply solutions for meeting zero emissions heating. There are likely to be inaccuracies in the specific numbers and the authors recommend further in-depth research would be required to address this question with more certainty.

Figure *15* and Figure *16* present a comparison of the CAPEX costs (£000's) and lifetime costs (£ms)[23]. Considering the CAPEX costs in isolation shows the increased upfront costs of delivering Passivhaus standard homes in Scenario 1. However, consideration of the full lifetime costs of each technology options suggest use of the direct wet and dry electric heating options to meet the minimal heating requirements of a Passivhaus building result in an overall cheaper lifetime cost than using lower levels of fabric efficiency with the same heating technology. Overall, however, use of ASHPs in a non-Passivhaus development still appears to be the lowest cost option on a lifetime cost basis.

Figure *17* presents the results of a sensitivity analysis to explore how this lifetime cost comparison might change if the 'additional costs of construction' for a Passivhaus were to reduce by 10%, 20% and 30%. The results suggest that even if the additional costs of delivering Passivhaus standard buildings were to reduce by 30% the lifetime costs of ASHPs in a non-Passivhaus development would still be marginally cheaper. However, given the level of error that is likely to be present in this cost analysis, further research is recommended before making conclusions on this point. In addition, it should be noted that the costs of grid upgrade costs associated with the development have not been included in the analysis. Were the development to be sited in a grid-constrained area, then the conclusions of this comparison are likely to change significantly.

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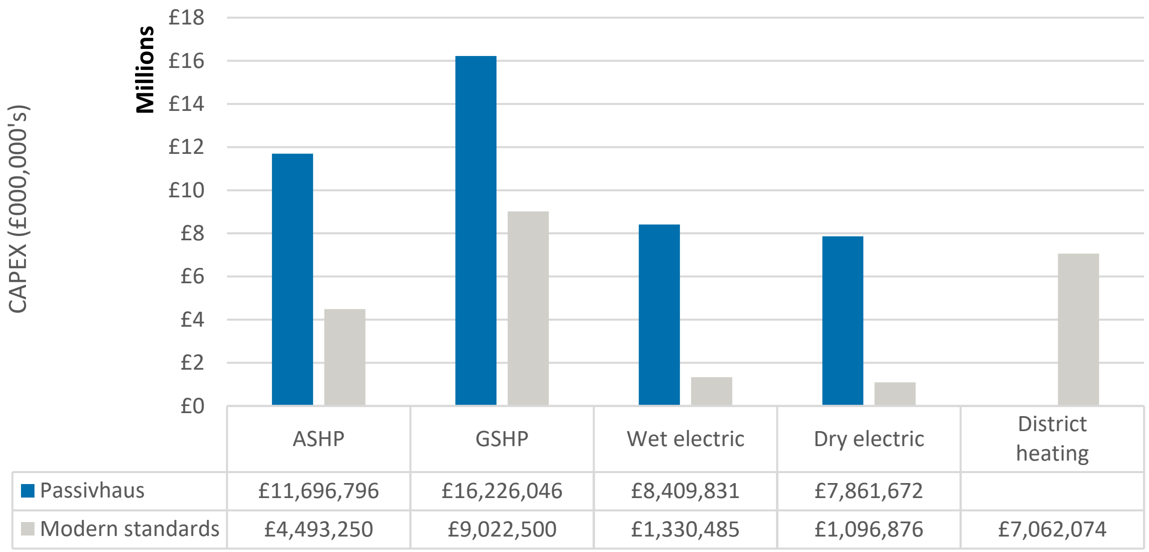
[23] The lifetime costs are not presented as a *levelised* lifetime cost in this section, but instead as the whole lifetime cost including CAPEX, REPEX, Maintenance and running costs. This is because the Passivhaus scenario costs include the 'addional' costs of fabric efficiency rather than only supply generation costs so it is not appropriate to consider costs per unit of heat supplied.



	ASHP	GSHP	Wet electric	Dry electric	District heating
■ Passivhaus	£11,696,796	£16,226,046	£8,409,831	£7,861,672	
■ Modern standards	£4,493,250	£9,022,500	£1,330,485	£1,096,876	£7,062,074

Figure 15: Comparison of the CAPEX costs (£000's) for 'Scenario 1: Private housing development' of delivering zero emissions heating with Passivhaus standards and reduced heat supply requirements (15kWh/m^2/year) vs. using modern building standards with larger heat supply requirements

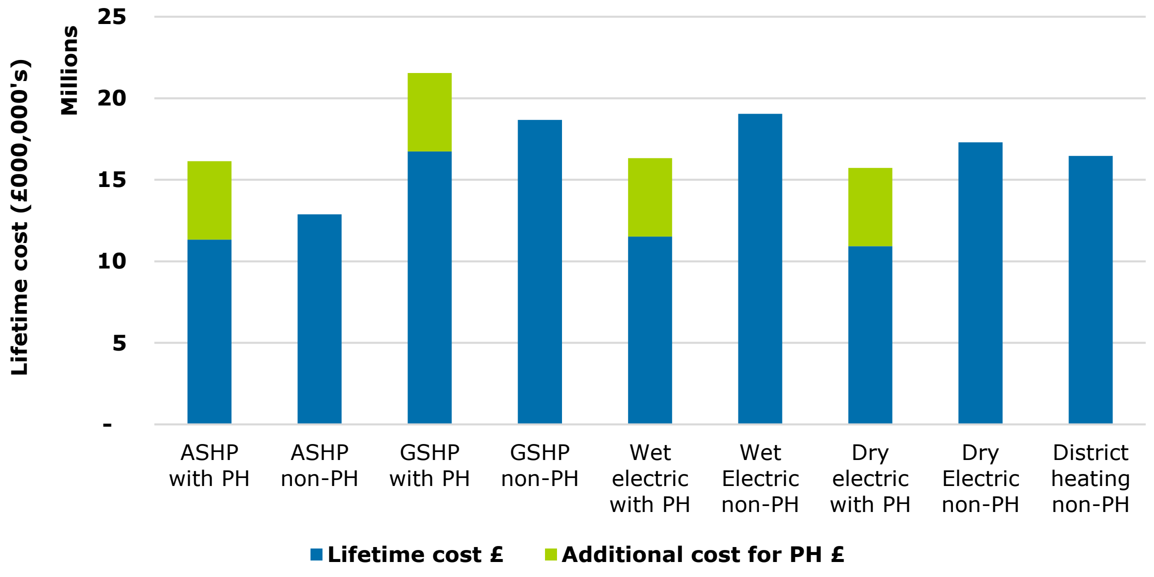


Figure 16: Comparison of the lifetime costs (£000,000s)) for 'Scenario 1: Private housing development' of delivering zero emissions heating with Passivhaus (PH) standards and reduced heat supply requirements (15kWh/m^2/year) vs. using modern building standards (non-PH) with larger heat supply requirements

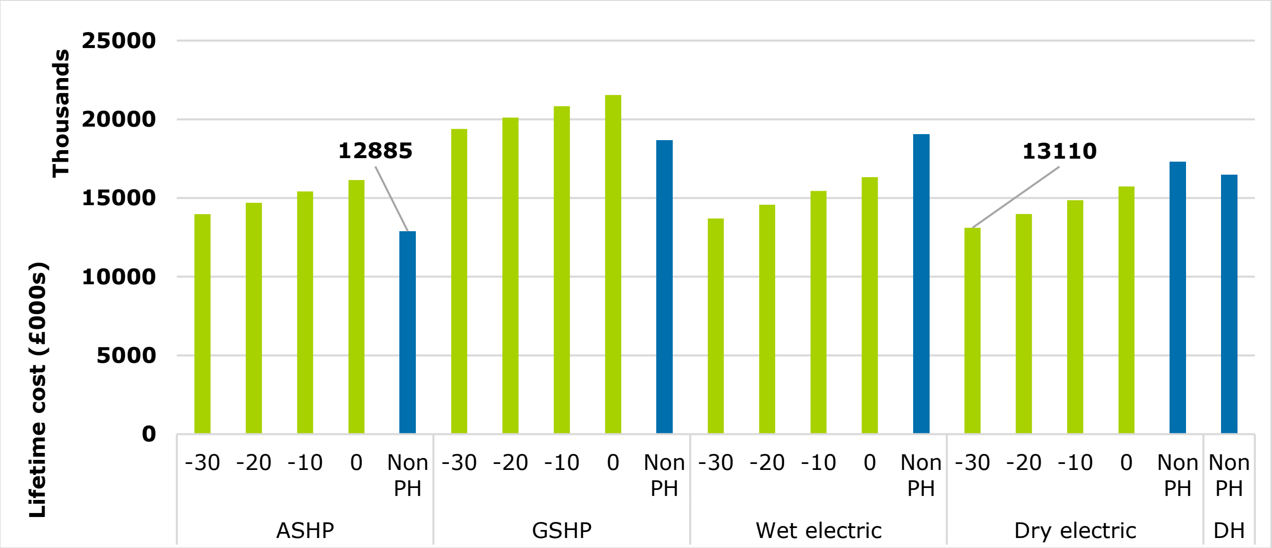


Figure 17: Sensitivity analysis to explore the impacts of varying the 'additional construction costs' of meeting Passivhaus standards by -10%, -20% and -30% on the lifetime costs (£000s) of each technology, compared to the lifetime costs in a non-passivhaus development (non-PH).

7 Conclusions and recommendations

This research has explored the costs of delivering zero emissions heating in six scenarios of new build developments, considering a range of both domestic and non-domestic new buildings. In all scenarios the use of zero emissions heating technology options represented lifetime cost increases ranging from 25%-231% compared to the equivalent cost of heat supply using gas boilers. However, giving consideration to the significant potential for cost reductions in zero emissions heating technologies over the coming decades, applying a sensitivity analysis to the technology CAPEX costs of 30% suggested lifetime cost increases as low as 6% compared to the equivalent cost of heat supply using gas boilers.

Key messages from stakeholder interviews:

- Delivering zero emissions heating was perceived as a significant change in existing development processes for some interviewees, and design and delivery processes were still being optimised and refined.
    - There was greater evidence of innovation in the social housing sector where policy drivers and the opportunities offered by zero emissions heating technologies to reduce costs to residents had led to development of compatible solutions and innovations ahead of the overall new build policy drivers such as the 2024 zero emissions heating standards. One interviewee commented that the private sector was now looking to the social housing sector to learn from their experiences of delivering zero emissions heating.
- The choice of technologies used in low carbon developments discussed in the stakeholder interviews were driven by more than just cost considerations. Commercial delivery models and the role that a developer played in a development after construction (e.g. taking on an operation and maintenance role in energy services, objectives to minimise occupant energy bills, etc) were also key factors in technology choices for zero emissions heating.
- This study identifies a potential gap in the sector for energy service organisations to deliver technology options with higher capital costs but lower running costs (i.e. optimising use of lowest lifetime cost). Such organisations, taking a long-term view

on the asset performance, are incentivised to optimise design, operation and maintenance over the lifetime of the system and thereby reduce whole life costs.
- Power grid upgrade costs were a significant concern to many of the stakeholders interviewed for this study and should be included in future analyses.

Key messages on technology costs

- There is a significant difference in the costs of zero emissions heating depending on whether it is considered in terms of CAPEX, electricity running costs or whole lifetime costs. The ‘cost-optimum’ technology option for each scenario therefore depends on the commercial delivery model of the developer as to whether they are concerned with the full lifetime cost of the technology (e.g. a build and operate delivery model), the CAPEX costs (e.g. a build to sell model), or running costs (e.g. a housing association seeking to reduce fuel poverty for tenants).
- Lifetime costs were significantly lower where developments could connect to an existing district heating network (considered in Scenarios 5 and 6). A new district heating network also appeared cost optimum in the high density, mixed-use development assumed in Scenario 2. Individual ASHPs appeared cost optimum on a lifetime cost basis in the remaining less dense developments (Scenarios 1, 3 and 4).
- For this analysis, where grid constraint costs were excluded from the analysis, wet and dry electric heating options offered a significantly lower capital cost, but lower upfront costs were offset by higher electricity running costs . However, these capital costs would be expected to increase where grid upgrades were required.
- There is potential for capital costs of the different heat pump technologies to reduce as a result of technology innovation, supply chain efficiencies through the anticipated scaling catalysed by agendas such as zero emissions heating in new builds etc., and the emergence of smart grids and energy storage solutions. Such market developments may improve the cost competitiveness of the heat pump zero emissions heating options but did not change the overall cost competitiveness of those options against other technology options in the scenarios and scope considered here. It should be noted, however, that the inclusion of grid upgrade costs could change the cost results significantly.
- An initial comparison analysis of Scenario 1: ‘Private Housing Development’ using Passivhaus design standards vs. less model fabric efficiency standards suggested that, on a lifetime cost basis, use of direct dry or wet electric heating systems with Passivhaus design offered the lowest cost option for delivering zero emissions heating.

Recommendations and further research:

- In the domestic sector, there are opportunities to learn from the social housing sector where piloting of innovation with different zero emissions heating technologies and trade-offs with energy efficiency have been going on for many years.
  - There are opportunities to reduce the overall costs of delivering zero emissions heating in new builds by ensuring existing district heating is connected into new build developments where there are opportunities to do so.
- A key area for further research is to understand how the inclusion of grid constraint upgrade costs would influence a cost comparison between technologies for the six scenarios.
- Similarly, it would be valuable to conduct further analysis to explore the lifetime costs of reaching higher energy efficiency levels within buildings vs. supplying zero emissions heating. The analysis conducted to consider the costs of reaching Passivhaus standards required a range of high-level assumptions that should be considered as an initial indication of results and would benefit from further refinement.

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9 Appendices

Appendix 1: Literature review search terms

Grey literature:

Zero carbon heating new build + technology by technology searches @

- UK Collaborative Centre for Housing Evidence
- ARUP
- CCC
- BEIS
- Scot Gov
- UK Gov
- E4Tech
- RICS
- Sustainable Energy Association
- IEA
- IRENA

Academic literature

Scotland

Google Scholar & Science Direct (range since 2012):

- zero carbon heating new build housing Scotland
- zero carbon heating Scotland
- zero carbon heating technologies Scotland
- zero carbon heating technologies new build housing Scotland
- zero carbon heating technologies costs Scotland
- zero carbon homes costs Scotland

UK

Google Scholar & Science Direct (range since 2012):

- zero carbon heating new build housing UK
- zero carbon heating new build housing costs UK
- zero carbon heating technologies UK
- zero carbon heating technologies costs UK
- zero carbon homes costs UK

International

Google Scholar & Science Direct (range since 2012):

- zero carbon heating new build housing
- zero carbon heating new build housing costs
- zero carbon heating technologies
- zero carbon heating technologies costs
- zero carbon homes costs

General
Google Scholar & Science Direct (range since 2012):

- zero carbon heating new build housing commercial models
- cost of zero carbon heat technologies new build housing

Appendix 2: Air source heat pumps (ASHPs)

Capital costs

The two types of ASHPs most referred to in the existing literature are air to air (aka air conditioning units) and air to water heat pumps.

- **Air to air heat pumps** can be effective for space heating in small dwellings where water heating demand is met by other means. Costs will depend on the size of property and subsequent sizing requirements. Costs could potentially be lower in new build properties if units were bought wholesale by developers. However, with regards to physical installation, there is little scope for cost reductions re new builds.
- The capital costs (including installation) for a one bedroom property which requires one 2KW (bedroom) and one 3.5KW unit (lounge) is reported to be around £2,400 (BEIS, 2018). However, this could increase to as much as £8,800 in a four-bedroom property (iBid). For greater detail regarding CAPEX see table below.
- With regards to OPEX and REPEX costs, there are a lack of hard figures in the existing literature. However, broadly speaking, OPEX will be largely influenced by electricity tariffs whilst REPEX is expected to be low (lower than conventional gas boilers for example) due to high reliability and system longevity (Staffell et al., 2012).
- Air to air heat pumps have high technological maturity and there is therefore little scope for cost reductions (iBid).

- **Air to water heat pumps** can meet both space and water requirements. Costs will depend on both the size and energy efficiency of the property which will determine sizing and system requirements. Costs are reported as being around 10% lower in new builds than retrofit properties (DECC, 2016). New builds can also take advantage of underfloor heating (which would be highly disruptive in a retrofit scenario).
- Capital costs quoted in the existing literature range from £5,000 to over £20,000 (BEIS, 2018; MacLean et al, 2016; Staffell et al., 2012; CCC, 2016). For example, a fully installed 8KW air to water heat pump including fittings, buffer tank, cylinder and controls but excluding the heat distribution system is quoted as costing around £8,750, whereas a 16KW system fully installed including fittings, large buffer tank and cylinder, advanced controls and heat distribution system could cost £21,550 (BEIS, 2018). For greater detail regarding CAPEX see table below.
- With regards to OPEX and REPEX costs, the existing literature tends to refer to the operational, maintenance and replacement benefits of air to water heat pumps without giving hard figures. For example, Staffell et al., 2012 (p9298) state that:

> *'Despite relatively high capital costs, heat pumps have in many cases passed the break-even point required to save money in the long run due to lower running costs and long operating lifetimes with minimal maintenance. Systems that are installed and operated correctly can provide lower fuel bills than a condensing boiler, while operation and maintenance (O&M) costs are also lower than for gas boilers due to reduced safety regulations and higher reliability. Electricity tends to be 3 to 4 times more expensive than the cheapest available domestic fuel (natural*

> *gas); however, the use of discounted heat pump or night-time electricity tariffs will reduce this ratio (known as the spark gap) substantially'*

- However, CCC (2016, p34) come to a different conclusion than that of Staffell et al (2012) highlighting uncertainty (exacerbated by the lack of hard figures):

> 'Electricity is around three times the price of gas. As heat pumps are around three times the efficiency of gas boilers, energy bills are likely to be similar after switching. This means that it is not possible to recoup the higher capital costs of the heat pump through reduced energy bills. This issue is likely to persist while carbon costs are not fully reflected in gas prices'

Opex and Repex cost

- Where costs have been attributed to OPEX and REPEX, this has been rolled into net costs in modelled scenarios, for example in BEIS (2019) and NIC (2018).
- Existing literature suggests that there is significant scope for costs reductions of air to water heat pumps, especially in the non-equipment sector. For example, DECC (2016) quote potential cost reductions of around 20%, made up of a 40% – 50% decrease in non-equipment costs and up to 10% reduction in equipment costs.
- Presently, installation is served by smaller companies who have high overheads. In the future smaller companies could be replaced by larger renewable energy specialists with smaller overheads helping to drive down costs to consumers (DECC, 2016).

Other considerations

- ASHP output is impacted by external temperature which means systems can struggle to meet heat demand in winter months. This can be mitigated by ensuring that properties have high energy efficiency or by pairing an ASHP with an auxiliary system (both of which can increase costs).
- As an electrification for heat decarbonisation option, mass roll out of ASHPs could put considerable strain on electricity infrastructure (especially low voltage local networks) which could result in the need for expensive grid upgrades in addition to increased storage requirements. This cost is included in several modelled scenarios including Maclean et al. (2016) which £2K per home network investment cost and >50,000 £/MWh for seasonal storage at the supply side.
- Current perceived barriers regarding ASHPs include: low consumer awareness; lack of confidence across supply chain; cost-intensive and sub-optimal supply chain; and, one-off installs which limit learning by doing (DECC, 2016; Staffell et al., 2012; BEIS, 2018).

Source	Specific Technology	CAPEX	OPEX	REPEX
Staffell, I. et al. (2012) ‘A review of domestic heat pumps’, Energy and Environmental Science, 5(11), pp. 9291–9306. doi: 10.1039/c2ee22653g	Air to Air	£1500–2000 (installed cost)	N/A	N/A
	Air to Water	£5000–7000 (installed cost)	N/A	N/A
Maclean et al. (2016) Managing Heat System Decarbonisation. Comparing the impacts and costs of transitions in heat infrastructure. [ONLINE] Available at: https://www.imperial.ac.uk/media/imperial-college/research-centres-and-groups/icept/Heat-infrastructure-paper.pdf. [Accessed 22 September 2020].	Does not state (Urban, Suburban and Rural – not suitable for flats)	£5000 - £15,000 (Appliance cost per household)	N/A	N/A
BEIS. (2018) The Cost of Installing Heating Measures in Domestic Properties. [ONLINE] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/913508/cost-of-installing-heating-measures-in-domestic-properties.pdf. [Accessed 23 September 2020].	8kW air source heat pump (Air-Water)	£ 8,750 (fully installed including fittings, buffer tank, cylinder and controls, excluding the heat distribution system)	N/A	N/A
	12.5kW air source heat pump (Air-Water)	£ 11,500 (fully installed including fittings, buffer tank, cylinder and heating controls, excluding the heat distribution system)	N/A	N/A
	16 kW air source heat pump (Air-Water)	£ 14,050 (fully installed including all new fittings, large buffer tank and advanced cylinder and controls (complex system)	N/A	N/A
	8kW air source heat pump (Air-Water)	£ 14,750 (fully installed including fittings, small buffer tank and cylinder, controls and heat distribution system (new for a smaller house)	N/A	N/A
	16kW air source heat pump (Air-Water)	£ 21,550 (fully installed including fittings, large buffer tank and cylinder, advanced controls and heat	N/A	N/A

		distribution system (new in larger house)		
	Air-Air (1 x 2 kW for bedroom + 1 x 3.5 kW for lounge)	£2,400 (1 bedroom flat)	N/A	N/A
	Air-Air (2 x 2kW for bedrooms + 1 x 3.5kW for lounge)	£4,000 (2 bedroom flat)	N/A	N/A
	Air-Air (3 x 2 kW for bedroom + 1 x 3.5 kW for lounge - large distance between indoor and outdoor units)	£6,500 (3 bedroom flat)	N/A	N/A
	Air-Air (4 x 2 kW for bedroom + 1 x 5 kW for lounge - large distance between indoor and outdoor units)	£8,800 (4 bedroom flat)	N/A	N/A
Committee on Climate Change. (2016) Next Steps for UK Heat Policy. [ONLINE] Available at: https://www.theccc.org.uk/publication/next-steps-for-uk-heat-policy/. [Accessed 24 September 2020]	Monobloc air-source heat pump	£5,700	N/A	N/A
	Split system air-source heat pump	£6,450	N/A	N/A

Appendix 3: Ground source (GSHPs) and water source heat pumps (WSHPs)

- Ground source heat pumps (GSHPs) are referred to more frequently in existing literature than water source heat pumps (WSHP).
- With regards to CAPEX, prices quoted in the existing literature range from £8,000 to almost £30,000. For example, Staffell et al (2012, p9297) quote £8,000–12,000 for a 10kW system installed cost ‘using a horizontal ground-loop lie at the lower end of these price ranges, and vertical borehole systems, installed with a new storage tank and other ancillary equipment lie at the high end’. However, BEIS (2018) quote £27,350 for a 12KW fully installed including buffer tank, cylinder, ground works, controls and the heat distribution with underfloor heating downstairs and radiators upstairs system. For greater detail regarding CAPEX see Appendix 4.
- According to DECC (2016, p4) <u>costs are around 10% lower in new builds</u>: ‘the overall split between equipment and non-equipment cost is relatively similar in new build as in retrofit – although overall costs tend to be lower. In new build developments where there are multiple GSHPs installed at the same site, the cost split shifts more towards equipment, as non- equipment costs per HP drop’. Installation in new builds also avoids significant disruption to consumers.
- Relatively high CAPEX of GSHPs is due to installation being significantly more disruptive (and expensive) than air source counterparts. Installation requires conductive pipe to be laid underground. The amount of pipe required will depend on the thermal conductivity of the soil. Pipe can be laid either horizontally with ground loops or vertically with boreholes. Horizontal ground loop installation requires a significant amount of land. Vertical installation requires a 100m – 150m borehole to be dug; this approach is highly site specific and requires a geological survey to be conducted to ascertain site feasibility.
- With regards to OPEX and REPEX costs, the existing literature tends to refer to the operational, maintenance and replacement benefits of ground to water heat pumps without giving hard figures (same as with ASHPs – see previous section for examples).
- Where costs have been attributed to OPEX and REPEX, this has been rolled in to net costs in modelled scenarios, for example in BEIS (2019) and NIC (2018).
- Existing literature suggests there is significant scope for cost reductions with DECC (2016, p4) reporting ‘an overall cost reduction of ~18% compared to current costs. This would be comprised of ~30% cost reduction in non-equipment costs, and 5-10% in equipment costs’. With regards to new builds a further ~5-10% reduction could be achieved due to volume purchases (iBid).
- Presently, installation is served by smaller companies who have high overheads. In the future smaller companies could be replaced by larger renewable energy specialists with smaller overheads helping to drive down costs to consumers (DECC, 2016).

- Unlike ASHP, GSHP output is not impacted by external temperature (temperature underground is relatively consistent year-round) which means systems can operate without the need for additional measures. Performance is optimal in energy efficient properties.
- However, alike ASHPs, as an electrification for heat decarbonisation option, mass roll out of GSHPs could put considerable strain on electricity infrastructure (especially low voltage local networks) which could result in the need for expensive grid upgrades.
- Factors that can influence the cost of GSHPs include: system sizing; equipment costs; non-equipment costs; oil prices (plastics); metal prices; load management applications may require investment to optimise control systems to provide flexibility; and, installers take larger margins. According to Karytsas and Theodoropoulou (2014, p49), from a consumer perspective: ‘knowledge concerning the use of a GSHP system for residential use is positively related to the existence in the residence of a person with an occupation or interests associated to environment, technology or engineering, as well as the awareness about RES2 issues and higher educational level’.
- Water source heat pumps (WSHP) are not referred to in existing literature to the same extent as ASHPs and GSHPs. They do not feature in recent UK grey lit documents commissioned by national government (from which much of the hard data cited in this review derives) and estimates of costs are hard to come by. However, according to Scot Gov (2017):

  ‘analysis of the Scotland Heat Map shows that an estimated 24% of domestic heat demand is within 1 kilometre of a major river. Water Source Heat Pumps (WSHP) can extract latent heat in rivers and use it to heat nearby homes and businesses. With almost a quarter of domestic demand situated near Scotland’s major waterways, WSHP technology has the potential to make an important contribution to decarbonising Scotland’s energy system’
- According to Burford, Onyango & Wright (2019, p41), ‘water source heat pumps are more efficient than air source heat pumps, but cost more and require more space outside’.
- When WSHPs are mentioned in existing literature, it is often in relation to their use as a heat source for district heating and cooling networks (see following section).

Source	***Technology***	***CAPEX***	***OPEX***	***REPEX***	***Comment***
Staffell, I. et al. (2012) ‘A review of domestic heat pumps’, Energy and Environmental Science, 5(11), pp. 9291–9306. doi: 10.1039/c2ee22653g.	Ground Source Heat Pump (doesn’t specify)	£8000–12,000 for a 10 kW system (installed cost - using a horizontal ground-loop lie at the lower end of these price ranges, and vertical borehole systems, installed with a new storage tank and other ancillary equipment lie at the high end)	N/A	N/A	If several systems are installed together neighbouring houses can take advantage of communal holes
BEIS (2018)	8kW ground source heat pump (ground – water)	£ 13,200 (fully installed including small buffer tank and cylinder but excluding ground works and excluding controls, excluding the heat distribution system)	N/A	N/A	
	12kW ground source heat pump (ground – water)	£ 14,850 (fully installed including buffer tank and cylinder but excluding ground works and excluding controls, excluding the heat distribution system)	N/A	N/A	
	16 KW ground source heat pump (ground – water)	£ 19,000 (fully installed including large buffer tank and cylinder, complex controls but excluding ground works and excluding the heat distribution system)	N/A	N/A	
	12 KW ground source heat pump (ground – water)	£ 20,850 (fully installed including buffer tank and cylinder and ground works, excluding the heat distribution system)	N/A	N/A	
	12 KW ground source heat pump (ground – water)	£ 27,350 (fully installed including buffer tank, cylinder, ground works, controls and the heat distribution (underfloor heating downstairs and radiators upstairs) system)	N/A	N/A	

Committee on Climate Change. (2016) Next Steps for UK Heat Policy. [ONLINE] Available at: https://www.theccc.org.uk/publication/next-steps-for-uk-heat-policy/. [Accessed 24 September 2020]	Does not state	£15,600			

Appendix 4: Heat networks/ district heating and cooling

- Heat networks (or district heating and cooling) are frequently cited in the existing literature as a decarbonisation of heat option. It is considered as both a retrofit and new build solution. The most recent iteration of heat networks are called 5th generation, however, the majority of existing literature is concerned with 4th generation (or even 3rd generation) technology. <u>There are no hard figures in the existing literature re the cost reductions associated with DHC for new build developments</u>. This may be related to the fact that within the existing literature heat pumps constitute the zero-carbon heating technology most associated with domestic new build homes (BEIS, 2018). This is due to the high operational efficiency of heat pumps in well insulated buildings; there is broad assumption within the existing literature that new build homes will have high energy efficiency (BEIS, 2018). Whereas, when considering heat networks, increasing the energy efficiency of the building stock can have a negative effect on viability if the network design is unaltered to capitalise on the opportunity to deploy schemes that operate at lower temperatures (CCC, 2015).
- According to the CCC (2015), DH (or DHC) is likely to be deployed more widely in the non-domestic sector due to their frequent geographical proximity to concentrations of high-density building and larger buildings acting as anchor loads.
- Both 4th and 5th generation technologies can reach high efficiencies at low operating temperatures (Buffa et al., 2019). However, 4G systems cannot provide both heating and cooling using the same pipes, whereas 5G systems (which are in the early stages of development) may be able to achieve this feat (iBid).
- However, according to the CCC (2015), demand for district cooling in the UK is perceived as low by key stakeholders. Indeed, there are only a handful of examples of recently developed buildings which utilise this technology (e.g. London Olympic Park and Salford Media City). Instead, most new build schemes utilise trigeneration (CCC, 2015).
- According to Lake, Rezaie, & Beyerlein (2017:421): ‘thermal networks were shown to be financially beneficial for the high-density buildings and complexes as well as densely populated urban areas and are defined by three main factors: production costs, network costs, and connection costs’
- With regards to CAPEX of 5th generation systems, pricing is extremely sensitive to site, residential and heat source specificities. However, to provide an example, ‘the additional capital costs per dwelling, for the installation of a 5GDHC system with respect to a conventional heating system, has been assessed to 5500 euros in Duindorp (Netherlands)’ (Buffa et al., 2019:507). For more details regarding costs see Appendix 5.
- With regards to OPEX and REPEX of 5th generation systems, there is not much data available in existing literature (owing in part to the relative novelty of the technology). However, for example Buffa et al., (2019:517) report ‘a total energy cost for the final user connected to a 5GDHC system equal to or less than the one of adopting a conventional heating and cooling system’. For more details regarding costs table below.

- It is also worth noting that: ‘with 5GDHC still being a recent and unexplored field, the know how about this technology is in the hands of few companies…No technical standards or guide-lines are available for designers and there is a lack of knowledge for 5GDHC operational optimization and control’ (Buffa et al., 2019:505).
- With regards to CAPEX of 4th generation systems, according to UK Gov (2016:11): ‘at current costs, the price of heat is likely to be significantly higher for district heating schemes incorporating heat pumps [as opposed to CHP] ...the premium for the price of heat for district heating schemes incorporating heat pumps is in the range 35-74%’. This is largely due to the high capital costs of heat pump technologies. However, it should be noted that ‘due to the low number of operational schemes, there is significant uncertainty around the cost of large, bespoke (MW-scale) heat pump systems’ (UK Gov, 2016:13). For more details regarding costs see table below.
- With regards to OPEX and REPEX estimates, where costs have been attributed this has been rolled in to net costs in modelled scenarios, for example in CCC (2015).
- With regards to cost reductions, the capital cost infrastructure of heat networks could reduce by between 30-40% (largely as a result of improving current practice incrementally by ‘learning by doing’ and innovation) (Catapult Energy Systems, 2018). However, there is little data concerning 5G systems.
- There are a multiplicity of factors which can influence the cost of DH in new builds including: energy source; options for co-generation; climate; geological specificities of site that impact upon borehole drilling; selection of a furnace/burner; heat exchanger selection; power failures; electricity prices; and, socio-political context (including policy environment) (Lake, Rezaie, & Beyerlein, 2017).
- The main driver for DH remains the density of cities.
- Barriers include: carbon saving is not reflected in the price of heating; natural monopoly; high fixed costs of district heat networks mean that it is more efficient for one operator to serve each local market; demand uncertainty; economies of scale mean that the viability of investments will be very sensitive to the level of demand secured; and, barriers associated with policy (Deasley, 2019).

Source	***Specific Technology***	***CAPEX***	***OPEX***	***REPEX***
Webb, J. (2015) 'Improvising innovation in UK urban district heating: The convergence of social and environmental agendas in Aberdeen', Energy Policy. Elsevier, 78, pp. 265–272. doi: 10.1016/j.enpol.2014.12.003.	CHP	Stockethill - 210 kWe - 300kWth - £1.8 million… Hazlehead - 300kWe - 488 kWth - £1.6 million… Seaton - 2100 kWe - 3000 kWth - £3.3 million… City Centre - £1 million	Heat tariffs for tenants are cost, rather than market-based (currently £10.54 per week, estimated as saving between 25% and 45% on electric heating for an equivalent dwelling).	N/A
Committee on Climate Change. (2015) Research on district heating and local approaches to heat decarbonisation. [ONLINE] Available at: https://d423d1558e1d71897434.b-cdn.net/wp-content/uploads/2015/11/Element-Energy-for-CCC-Research-on-district-heating-and-local-approaches-to-heat-decarbonisation.pdf. [Accessed 24 September 2020].	River Source Heat Pump (Low Scenario)[24]	£750,000 (£/MWth) (2015) £600,000 (£/MWth) (2030) £525,000 (£/MWth) (2050)	£3,750 (£2014/MWth) (All years)	N/A
	River Source Heat Pump (Central Scenario)	£1,500,000 (£/MWth) (2015) £1,200,000 (£/MWth) (2030) £1,050,000 (£/MWth) (2050)	£7,500 (£2014/MWth) (All years)	N/A
	River Source Heat Pump (High Scenario)	£2,000,000 (£/MWth) (2015) £1,600,000 (£/MWth) (2030) £1,400,000 (£/MWth) (2050)	£10,000 (£2014/MWth) (All years)	N/A
	Sewage Source Heat Pump (Low Scenario)	£900,000 (£/MWth) (2015) £720,000 (£/MWth) (2030) £630,000 (£/MWth) (2050)	£4,500 (£2014/MWth) (All years)	N/A

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[24] According to CCC (2015:6): 'The three scenarios reflect different levels of policy intervention to incentivise and assist the roll-out of district heating in the UK'.

	Sewage Source Heat Pump (Central Scenario)	£1,800,000 (£/MWth) (2015) £1,440,000 (£/MWth) (2030) £1,260,000 (£/MWth) (2050)	£9,000 (£2014/MWth) (All years)	N/A
	Sewage Source Heat Pump (High Scenario)	£2,400,000 (£/MWth) (2015) £1,920,000 (£/MWth) (2030) £1,680,000 (£/MWth) (2050)	£12,000 (£2014/MWth) (All years)	N/A
	Industrial Waste Heat Source Pump (Low Scenario)	£525,000 (£/MWth) (2015) £420,000 (£/MWth) (2030) £367,000 (£/MWth) (2050)	£2,625 (£2014/MWth) (All years)	N/A
	Industrial Waste Heat Source Pump (Central Scenario)	£1,050,000 (£/MWth) (2015) £840,000 (£/MWth) (2030) £735,000 (£/MWth) (2050)	£5,250 (£2014/MWth) (All years)	N/A
	Industrial Waste Heat Source Pump (High Scenario)	£1,400,000 (£/MWth) (2015) £1,120,000 (£/MWth) (2030) £980,000 (£/MWth) (2050)	£7,000 (£2014/MWth) (All years)	N/A
	Thermal Power Station Heat Source Heat Pump (Low Scenario)	£525,000 (£/MWth) (2015) £420,000 (£/MWth) (2030) £367,000 (£/MWth) (2050)	£2,625 (£2014/MWth) (All years)	N/A
	Thermal Power Station Heat Source Heat Pump (Central Scenario)	£1,050,000 (£/MWth) (2015) £840,000 (£/MWth) (2030) £735,000 (£/MWth) (2050)	£5,250 (£2014/MWth) (All years)	N/A
	Thermal Power Station Heat Source Heat Pump (High Scenario)	£1,400,000 (£/MWth) (2015) £1,120,000 (£/MWth) (2030) £980,000 (£/MWth) (2050)	£7,000 (£2014/MWth) (All years)	N/A
	Biomass Boiler (Low Scenario)	£351,705 (£/MWth) (2015) £316,535 (£/MWth) (2030) £316,535 (£/MWth) (2050)	£17,585 (£2014/MWth) (All years)	N/A

	Biomass Boiler (Central Scenario)	£410,508 (£/MWth) (2015) £369,457 (£/MWth) (2030) £369,457 (£/MWth) (2050)	£20,525 (£2014/MWth) (All years)	N/A
	Biomass Boiler (High Scenario)	£469,310 (£/MWth) (2015) £422,379 (£/MWth) (2030) £422,379 (£/MWth) (2050)	£23,466 (£2014/MWth) (All years)	N/A
	Thermal Storage (Low Scenario)	£36,000 (£/MWth) (2015) £36,000 (£/MWth) (2030) £36,000 (£/MWth) (2050)	£0 (£2014/MWth) (All years)	N/A
	Thermal Storage (Central Scenario)	£41,000 (£/MWth) (2015) £41,000 (£/MWth) (2030) £41,000 (£/MWth) (2050)	£0 (£2014/MWth) (All years)	N/A
	Thermal Storage (High Scenario)	£46,000 (£/MWth) (2015) £46,000 (£/MWth) (2030) £46,000 (£/MWth) (2050)	£0 (£2014/MWth) (All years)	N/A
	Heat Interface Unit (HIU) and Heat Meter – Domestic (Low Scenario)	£1,700 (per dwelling) (2015) £1,518 (per dwelling) (2030) £1,275 (per dwelling) (2050)	£51 (£2014/MWth) (All years)	N/A
	Heat Interface Unit (HIU) and Heat Meter – Domestic (Central Scenario)	£2,000 (per dwelling) (2015) £1,786 (per dwelling) (2030) £1,500 (per dwelling) (2050)	£60 (£2014/MWth) (All years)	N/A
	Heat Interface Unit (HIU) and Heat Meter – Domestic (High Scenario)	£2,300 (per dwelling) (2015) £2,300 (per dwelling) (2030) £2,300 (per dwelling) (2050)	£69 (£2014/MWth) (All years)	N/A

	Upgrade Emitters for Low T Network – Domestic (Low Scenario)	£0 (per dwelling) (2015) £0 (per dwelling) (2030) £0 (per dwelling) (2050)	£0 (£2014/MWth) (All years)	N/A
	Upgrade Emitters for Low T Network – Domestic (Central Scenario)	£3,969 (per dwelling) (2015) £3,969 (per dwelling) (2030) £3,969 (per dwelling) (2050)	£0 (£2014/MWth) (All years)	N/A
	Upgrade Emitters for Low T Network – Domestic (High Scenario)	£5,670 (per dwelling) (2015) £5,670 (per dwelling) (2030) £5,670 (per dwelling) (2050)	£0 (£2014/MWth) (All years)	N/A
	Heat Interface Unit (HIU) and Heat Meter – Non-Domestic (Low Scenario)	£1,928 (per connect) (2015) £1,721 (per connect) (2030) £1,446 (per connect) (2050)	£58 (£2014/MWth) (All years)	N/A
	Heat Interface Unit (HIU) and Heat Meter – Non-Domestic (Central Scenario)	£2,268 (per connect) (2015) £2,025 (per connect) (2030) £1,701 (per connect) (2050)	£68 (£2014/MWth) (All years)	N/A
	Heat Interface Unit (HIU) and Heat Meter – Non-Domestic (High Scenario)	£2,608 (per connect) (2015) £2,608 (per connect) (2030) £2,608 (per connect) (2050)	£78 (£2014/MWth) (All years)	N/A
	Upgrade Emitters for Low T Network – Non-Domestic (Low Scenario)	£0 (per connect) (2015) £0 (per connect) (2030) £0 (per connect) (2050)	£0 (£2014/MWth) (All years)	N/A
	Upgrade Emitters for Low T Network – Non-Domestic (Central Scenario)	£3,969 (per connect) (2015) £3,969 (per connect) (2030) £3,969 (per connect) (2050)	£0 (£2014/MWth) (All years)	N/A
	Upgrade Emitters for Low T Network – Non-Domestic (High Scenario)	£5,670 (per connect) (2015) £5,670 (per connect) (2030) £5,670 (per connect) (2050)	£0 (£2014/MWth) (All years)	N/A

	Transmission, Distribution and Service Pipe Costs: <25 mm pipe radius (Low Scenario)	£559 p/metre length (2015) £523 p/metre length (2030) £479 p/metre length (2050)	£2 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 0 - 25 mm pipe radius (Low Scenario)	£565 p/metre length (2015) £529 p/metre length (2030) £480 p/metre length (2050)	£2 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 25 - 32 mm pipe radius (Low Scenario)	£605 p/metre length (2015) £566 p/metre length (2030) £514 p/metre length (2050)	£2 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 32 - 40 mm pipe radius (Low Scenario)	£631 p/metre length (2015) £590 p/metre length (2030) £536 p/metre length (2050)	£3 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 40 - 50 mm pipe radius (Low Scenario)	£703 p/metre length (2015) £658 p/metre length (2030) £598 p/metre length (2050)	£3 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 50 - 65 mm pipe radius (Low Scenario)	£729 p/metre length (2015) £683 p/metre length (2030) £620 p/metre length (2050)	£3 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 65 - 80 mm pipe radius (Low Scenario)	£795 p/metre length (2015) £744 p/metre length (2030) £676 p/metre length (2050)	£3 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 80 - 100 mm pipe radius (Low Scenario)	£874 p/metre length (2015) £818 p/metre length (2030)	£3 (£2014/metre length) (All years)	N/A

		£743 p/metre length (2050)		
	Transmission, Distribution and Service Pipe Costs: 100 - 125 mm pipe radius (Low Scenario)	£943 p/metre length (2015) £883 p/metre length (2030) £802 p/metre length (2050)	£4 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 125 – 150 mm pipe radius (Low Scenario)	£1,091 p/metre length (2015) £1,021 p/metre length (2030) £927 p/metre length (2050)	£4 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 150 – 200 mm pipe radius (Low Scenario)	£1,252 p/metre length (2015) £1,172 p/metre length (2030) £1,064 p/metre length (2050)	£5 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 200 - 250 mm pipe radius (Low Scenario)	£1,406 p/metre length (2015) £1,316 p/metre length (2030) £1,195 p/metre length (2050)	£6 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 250 - 300 mm pipe radius (Low Scenario)	£1,715 p/metre length (2015) £1,605 p/metre length (2030) £1,458 p/metre length (2050)	£7 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 300 - 400 mm pipe radius (Low Scenario)	£2,023 p/metre length (2015) £1,893 p/metre length (2030) £1,720 p/metre length (2050)	£8 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: >600 mm pipe radius (Low Scenario)	£2,104 p/metre length (2015) £1,969 p/metre length (2030) £1,788 p/metre length (2050)	£8 (£2014/metre length) (All years)	N/A

	Transmission, Distribution and Service Pipe Costs: <25 mm pipe radius (Central Scenario)	£559 p/metre length (2015) £541 p/metre length (2030) £517 p/metre length (2050)	£2 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 0 - 25 mm pipe radius (Central Scenario)	£565 p/metre length (2015) £547 p/metre length (2030) £523 p/metre length (2050)	£2 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 25 - 32 mm pipe radius (Central Scenario)	£605 p/metre length (2015) £585 p/metre length (2030) £559 p/metre length (2050)	£2 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 32 - 40 mm pipe radius (Central Scenario)	£631 p/metre length (2015) £611 p/metre length (2030) £584 p/metre length (2050)	£3 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 40 - 50 mm pipe radius (Central Scenario)	£703 p/metre length (2015) £681 p/metre length (2030) £650 p/metre length (2050)	£3 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 50 - 65 mm pipe radius (Central Scenario)	£729 p/metre length (2015) £706 p/metre length (2030) £675 p/metre length (2050)	£3 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 65 - 80 mm pipe radius (Central Scenario)	£795 p/metre length (2015) £770 p/metre length (2030) £736 p/metre length (2050)	£3 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 80 - 100 mm pipe radius (Central Scenario)	£874 p/metre length (2015) £846 p/metre length (2030)	£3 (£2014/metre length) (All years)	N/A

		£808 p/metre length (2050)		
	Transmission, Distribution and Service Pipe Costs: 100 - 125 mm pipe radius (Central Scenario)	£943 p/metre length (2015) £913 p/metre length (2030) £873 p/metre length (2050)	£4 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 125 – 150 mm pipe radius (Central Scenario)	£1,091 p/metre length (2015) £1,056 p/metre length (2030) £1,009 p/metre length (2050)	£4 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 150 – 200 mm pipe radius (Central Scenario)	£1,252 p/metre length (2015) £1,212 p/metre length (2030) £1,158 p/metre length (2050)	£5 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 200 - 250 mm pipe radius (Central Scenario)	£1,406 p/metre length (2015) £1,361 p/metre length (2030) £1,301 p/metre length (2050)	£6 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 250 - 300 mm pipe radius (Central Scenario)	£1,715 p/metre length (2015) £1,660 p/metre length (2030) £1,587 p/metre length (2050)	£7 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 300 - 400 mm pipe radius (Central Scenario)	£2,023 p/metre length (2015) £1,958 p/metre length (2030) £1,871 p/metre length (2050)	£8 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: >600 mm pipe radius (Central Scenario)	£2,104 p/metre length (2015) £2,036 p/metre length (2030) £1,946 p/metre length (2050)	£8 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: <25 mm pipe radius (High Scenario)	£559 p/metre length (2015) £559 p/metre length (2030) £559 p/metre length (2050)	£2 (£2014/metre length) (All years)	N/A

	Transmission, Distribution and Service Pipe Costs: 0 - 25 mm pipe radius (High Scenario)	£565 p/metre length (2015) £565 p/metre length (2030) £565 p/metre length (2050)	£2 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 25 - 32 mm pipe radius (High Scenario)	£605 p/metre length (2015) £605 p/metre length (2030) £605 p/metre length (2050)	£2 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 32 - 40 mm pipe radius (High Scenario)	£631 p/metre length (2015) £631 p/metre length (2030) £631 p/metre length (2050)	£3 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 40 - 50 mm pipe radius (High Scenario)	£703 p/metre length (2015) £703 p/metre length (2030) £703 p/metre length (2050)	£3 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 50 - 65 mm pipe radius (High Scenario)	£729 p/metre length (2015) £729 p/metre length (2030) £729 p/metre length (2050)	£3 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 65 - 80 mm pipe radius (High Scenario)	£795 p/metre length (2015) £795 p/metre length (2030) £795 p/metre length (2050)	£3 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 80 - 100 mm pipe radius (High Scenario)	£874 p/metre length (2015) £874 p/metre length (2030) £874 p/metre length (2050)	£3 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 100 - 125 mm pipe radius (High Scenario)	£943 p/metre length (2015) £943 p/metre length (2030) £943 p/metre length (2050)	£4 (£2014/metre length) (All years)	N/A

	Transmission, Distribution and Service Pipe Costs: 125 – 150 mm pipe radius (High Scenario)	£1,091 p/metre length (2015) £1,091 p/metre length (2030) £1,091 p/metre length (2050)	£4 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 150 – 200 mm pipe radius (High Scenario)	£1,252 p/metre length (2015) £1,252 p/metre length (2030) £1,252 p/metre length (2050)	£5 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 200 - 250 mm pipe radius (High Scenario)	£1,406 p/metre length (2015) £1,406 p/metre length (2030) £1,406 p/metre length (2050)	£6 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 250 - 300 mm pipe radius (High Scenario)	£1,715 p/metre length (2015) £1,715 p/metre length (2030) £1,715 p/metre length (2050)	£7 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: 300 - 400 mm pipe radius (High Scenario)	£2,023 p/metre length (2015) £2,023 metre length (2030) £2,023 metre length (2050)	£8 (£2014/metre length) (All years)	N/A
	Transmission, Distribution and Service Pipe Costs: >600 mm pipe radius (High Scenario)	£2,104 p/metre length (2015) £2,104 p/metre length (2030) £2,104 p/metre length (2050)	£8 (£2014/metre length) (All years)	N/A

Appendix 5: Zero carbon buildings (ZCBs)/ zero carbon homes (ZCHs)

- There is a significant amount of existing literature which investigates zero carbon homes.
- Zero carbon homes as consisting of one or a mix of: (1) good fabric energy efficiency, (2) onsite low/zero carbon heat and power technologies, or (3) allowable solutions to compensate carbon emission reductions.
- According to Zhao, Huang & Lu (2018:1214): ‘although ZCBs are espoused in many policy circles and many examples have been constructed to demonstrate their technical feasibility, there is a scarcity of evidence demonstrating economical rational, particularly for large scale housing development. This knowledge gap is significant as the selection of zero carbon technologies by developers is predominantly driven by their technical and economic attributes’.
- In Scotland and the UK, perhaps the most cited form of zero carbon housing is Passivhaus standard. The Passivhaus Trust (2019) quote CAPEX for a Passivhaus certified property in the UK at £1,465/m2, this is in comparison to a baseline figure of £1,325/m2. Similarly, according to the Passivhaus Institut (2012:4), a Passivhaus certified new build property in the UK requires ‘15% extra investment... The difference in capital expenditure is expected to be significantly lower on a larger development, where economies of scale and more efficient design typologies can be exploited’. Furthermore, the report just quoted also provides elemental costs breakdown for the constituent components of a Passivhaus including: substructure; superstructure; internal finishes; fittings and furnishings; M&E installations; and, on-costs. For more details regarding costs see table below.
- With regards to OPEX and REPEX, most of the existing literature is concerned with capital costs and does not give hard figures for operation, maintenance and replacement. However, broadly speaking, the benefits of Passivhaus standard properties include: energy saving leading to fuel poverty eradication; reduced maintenance and lifecycle costs; reduced rent arrears & voids; fewer complaints arising from noise issues; market value increase (rent & sale capital); and, future-proofed resulting in less ongoing capital investment (Mitchell & Natarajan, 2020).
- With regards to potential cost reductions, The Passivhaus Trust (2019:12) state that: ‘there is no reason why the economies of scale available in the commercial housebuilding model would not be equally applicable to mass construction to Passivhaus, provided Passivhaus became the norm’.
- With regards to perceived barriers and factors that can impact costs: there is an insufficient volume from any single source (commissioning body) to drive a standard design or a standard approach (Passivhaus Trust, 2019); the geographic spread of projects across the country has not exposed the supply chain to the practice required, so there is very limited skills-building, experience or learning being generated (iBid); there are reports of performance gaps, however, there is conflicting evidence in the existing literature regarding the extent to which this constitutes a serious problem for Passivhaus construction in Scotland and the UK. For example, Mitchell & Natarajan (2020:9) state that:

‘compliance with the Passivhaus standard delivers low-energy homes, with no performance gap’, whereas Foster et al., (2016:2) state that ‘the performance gap between “as designed” and “as built” is increasingly well evidenced’ (they cite a Zero Carbon Hub 2014 report as evidence).

- Although Passivhaus is the most frequently cited zero carbon home standard, existing literature also considers ‘tighter standards for new buildings’ (CCC, 2019). For example, (iBid) considers the additional capital costs for each dwelling type [4 archetypes used] of achieving varying space heating demands in combination with different heating systems in 2020: heating and hot water; ventilation; air tightness; glazing; fabric; and, net capital cost impact. For more details regarding costs table below. In their analysis, the CCC conclude that ‘none of the scenarios represent an overall lifetime cost saving, in the absence of considering the value of the carbon saved… but tighter standards and low-carbon heat can result in reductions in running costs for households of up to an annualised £87 per year over 60 years’ (iBid:51).
- It is reported that there is little correlation between dwelling energy demand and the appropriateness and scale of the LZCGTs specified. This can impact upon costs significantly (Burford, Onyango, & Wright, 2019).
- The adoption of a particular LZCGT appears to be driven by individual applicant and not by any specific regional or local policy, which means that the lack of strategic policies in relation to regional and local energy contexts may be limiting greater CO2 emissions reductions (iBid).
- It is also worth drawing attention to research which suggests that: ‘actors and platforms acting as innovation intermediaries advance zero carbon buildings at different stages of project development, with varying intensity, influence and longevity’ (Martiskainen & Kivimaa, 2018:15).

Source	***Specific Technology***	***CAPEX***	***OPEX***	***REPEX***
The Passivhaus Trust. (2019) Passivhaus Construction Costs. [ONLINE] Available at: http://passivhaustrust.org.uk/UserFiles/File/research%20papers/Costs/2019.10_Passivhaus%20Costs(1).pdf. [Accessed 21 September 2020].	Passivhaus Standards	£1,465/m2	N/A	N/A
Passivhaus Institut. (2012) Passivhaus cost comparison in the context of UK Regulation and prospective market incentives. [ONLINE] Available at: https://www.bere.co.uk/assets/NEW-r-and-d-attachments/Larch-and-Lime-Houses-Passivhaus-Cost-Comparison-2012.pdf. [Accessed 21 September 2020].	Passivhaus Standards	15% extra investment for passivhaus standard (The difference in capital expenditure is expected to be significantly lower on a larger development, where economies of scale and more efficient design typologies can be exploited (e.g. terrace or low rise apartment))	N/A	N/A
Committee on Climate Change. (2019) The costs and benefits of tighter standards for new buildings. [ONLINE] Available at: https://www.theccc.org.uk/wp-content/uploads/2019/07/The-costs-and-benefits-of-tighter-standards-for-new buildings-Currie-Brown-and-AECOM.pdf.	Tighter standards for new building	**Semi-detached Key Findings:** Additional costs of the more energy efficient standards are between 3% to 5% of total build costs. The additional cost of tighter space heating standards are predominantly a result of fabric improvements and introduction of an MVHR unit A significant (up to c.£2,000) saving in the capital cost of the heating distribution system helps to offset the additional costs associated with the most energy efficient fabric specifications.	N/A	N/A

[Accessed 22 September 2020].		The additional costs of installing an ASHP in place of a gas boiler are c.£2,500, this includes for the heat pump, power supply, hot water store and larger low temperature radiators, the additional cost includes a saving of c.£350 per home for avoided gas connection costs. **Detached Key Findings:** Fabric improvement costs are higher for a detached than the semi-detached home. This is a result of the larger external area both in absolute terms and relative to the internal floor area. For example, to achieve space heating demand of 15kWh/m2/yr in a detached house it is necessary to have external wall U values of 0.13 W/m2 K even with an air tightness of 1m3m2hr; in a semi-detached house with equivalent airtightness it is possible to achieve this standard with a wall U value of 0.21 W/m2 K. A £3,300 saving in the capital cost of the heating distribution system helps to offset the additional costs associated with the most energy efficient fabric specifications. Costs of installing an ASHP are lower than for a semi-detached home. This is because a 4-bed home would typically include a system boiler and hot water store and so the additional costs of installing as store as part of the ASHP system would only require that the store is compatible with a lower temperature water source, i.e. it has a larger heat exchange surface. This is one of the future-proofing measures recommended in new homes **Large Low-Rise Flat Key Findings:** In contrast to the assessed houses, the route to achieving lower space heating demand in flats primarily involves the use of MVHR systems and some improvements in glazing standards. Improved airtightness, glazing and ventilation can even result in the U values for external walls being relaxed to levels that are less insulating and less expensive than the Part L notional specification. The additional cost of reducing space heat demand is smaller (at under 1.5% of capital costs) than for housing, although the absolute reduction in heat demand is also smaller as the Part L notional specification has a demand of 33kWh/m2/yr.		

		Another variation for this low-rise flat archetype is the relatively small uplift impact of installing an ASHP. This is in part because of the avoided cost of a gas connection which is estimated at c.£1,100 per home - higher than that for housing. The cost uplift for connection to a heat network is proportionately higher than for other house archetypes as a result of the need for centralised heat interface units, pumps and controls to draw heat from the network and then further heat interface units within each dwelling. **Small High Rise Flat Key Findings:** As with the large (low rise) flat, reductions in space heating demand are primarily achieved using heat recovery ventilation systems, and where these technologies are used it is possible to slightly reduce the specification of the external walls. The percentage cost uplift for achieving the lowest levels of space heating demand are lowest for this dwelling type. This is because the construction cost of the small (high rise) flat is higher than other homes while the level of energy efficiency needed to achieve a 15kWh/m2/yr target is relatively small as its highly efficient form factor means that the heating demand when built to the Part L Notional specification is only 26kWh/m2/yr. The costs of using either an ASHP or a LCHN connection are lower than for other dwelling types with the capital costs of a LCHN being lower than for the gas boiler equivalent. This is because the gas heated base case is higher than for other homes because it includes for a centralised heating system with storage and heat interface units in each property. The additional costs of adding an ASHP to the generation plant are therefore smaller and in the case of the LCHN ability to replace generation plant with a block level heat interface unit represents a small cost saving.		
Berry, S. and Davidson, K. (2015) 'Zero energy homes - Are they economically viable?', Energy Policy. Elsevier, 85, pp. 12–21. doi: 10.1016/j.enpol.2015.05.009.	Zero energy homes	Research shows that existing building designs at NatHERS 5 or 6 Star can be altered to achieve higher energy (thermal comfort) performance at a net reduction or a trivial (AUD$0–$500) increase in construction costs (Sustainability House, 2012a, 2012b), through simple changes to the glazing, insulation, and shading specifications. To reach beyond around 7 Stars may need a step change in technology to insulating glass (i.e. double glazing) at a higher unit cost. Currently the application of double glazing in residential homes is atypical in warm temperate Australian climates. Construction cost estimators	N/A	N/A

		(Cordell Information Services, 2013; Rawlinsons Group, 2013) list the price difference between single and double glazed windows to be between 169% and 184% in 2013. For this study, it is assumed that all living room and bedroom windows will be upgraded (maximum 30 m2 glazing), with a net increase of $3000 for changes to glazing and shading specifications. A further $500 is allocated for the additional cost to install higher specification wall or ceiling insulation... Studies have shown that when heating and cooling loads are reduced, the system type and size can be changed with consequent cost reductions (Elberling and Bourne, 1996; Energy Efficient Strategies, 2001). The RIS for the proposed changes to the 2010 BCA (Australian Building Codes Board, 2009) estimated the average reverse cycle heating/cooling system capacity at 5.4 kW, and considered that a 1 kW reduction in capacity to equate to $200 in reduced heating/cooling plant, but discounted that saving by 50% to account for market rigidities. The Lochiel Park Urban Design Guidelines restrict heating/cooling system capacity for a medium size house to a maximum of approximately 3 kW. For the purpose of this study, the reduction in plant is assumed to be 2 kW with an associated cost reduction of $200... A change of the proposed lighting density standard to 3 W/m2 is not expected to increase lighting system or maintenance costs. This is consistent with the finding of the 2010 BCA RIS which considered a reduction to 5 W/m2 for fixed lighting capacity would not increase construction costs (Australian Building Codes Board, 2009). Typical energy efficient products available in the Australian market such as CFLs (9–15 W) are available for a similar or lower price than alternative halogen dichroic (35/50 W) products... The current building energy standard requires, for a typical new home, a solar or heat pump product of at least 26 STCs, or a gas system with a greenhouse gas intensity of no greater than 100 g CO2-e/MJ (Australian Building Codes Board, 2014). The pro- posed standard increases the minimum to 40 STCs, and would mean a change in the typical system from a gas boosted solar storage product or an instantaneous gas system to an instantaneous gas boosted solar product. Cost estimators nominate the cost difference between a gas storage heater and a solar sysem in 2013 to be $2200 (Rawlinsons Group, 2013), or $1050 to add an instantaneous gas system to an existing storage solar sys- tem. Although basic level solar water heating products are relatively mature in their development cycle, it is assumed that there is scope for product development		

		and increased production volume for higher performance products. For the purpose of this study the average additional cost of changing to the 40 STC rated water heater will be $1750, and the assumed learning rate to be 18% per each doubling of production... To meet the net zero energy standard the average new home (200 m2) will need a 4.75 kWp photovoltaic system at an assumed installed cost of $8321 (extrapolated from the December 2013 average cost). The PV modules are considered to have an effective life of 30 years... Given that the same regulatory processes, industry design processes and energy performance assessment tool (i.e. NatHERS) will be used to determine compliance as is required at the current BCA levels for thermal comfort, lighting and water heating; compliance costs are not expected to increase...		
Passivhaus Institut. (2012) Passivhaus cost comparison in the context of UK Regulation and prospective market incentives. [ONLINE] Available at: https://www.bere.co.uk/assets/NEW-r-and-d-attachments/Larch-and-Lime-Houses-Passivhaus-Cost-Comparison-2012.pdf.	Substructure: Foundations	(1) [25]£1159.76 (2) [26]£3501.43	N/A	N/A
	Substructure: Basement Excavation	(1) £0 (2) £0	N/A	N/A
	Substructure: Basement Retaining Walls	(1) £0 (2) £0	N/A	N/A
	Substructure: Ground Floor Construction	(1) £6232.76 (2) £3209.08	N/A	N/A

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[25] 'The Passivhaus model specification was adjusted to the 'GB Manchester' standard weather data set, thought to be suitably representative of the UK average climate for the purposes of the research. The specification of the model house was reduced to meet the Passivhaus 'optimum' heat load of 10W/m2' (Passivhaus Institut, 2012)

[26] 'A second test model was subjected to further reductions in fabric performance to create a building which 'just' met the fabric criteria of Part L 2010 UK building regulations. Junctions were also adjusted to reflect typical UK construction practice using 'accredited construction details' from government guidance' (Passivhaus Institut, 2012)

[Accessed 21 September 2020].	Superstructure: Frame	(1) £14,601.60 (2) £13,863.58	N/A	N/A
	Superstructure: Upper Floors	(1) £341.45 (2) £341.45	N/A	N/A
	Superstructure: Roof	(1) £5211.82 (2) £4424.28	N/A	N/A
	Superstructure: Stairs	(1) £546 (2) £546	N/A	N/A
	Superstructure: External Walls	(1) £11,336.03 (2) £7,784.61	N/A	N/A
	Superstructure: Windows and External Doors	(1) £16,451.46 (2) £11,241.24	N/A	N/A
	Superstructure: Internal Walls and Partition	(1) £4,274.64 (2) £4,274.64	N/A	N/A
	Superstructure: Internal Doors	(1) £2,579.54 (2) £2,579.54	N/A	N/A
	Internal Finishes: Wall Finishes	(1) £4,569.72 (2) £4,569.72	N/A	N/A
	Internal Finishes: Floor Finishes	(1) £4,376.12 (2) £4,376.12	N/A	N/A
	Internal Finishes: Ceiling Furnishes	(1) £2,455.39 (2) £2,455.39	N/A	N/A
	Fittings and Furnishings: General Fittings, Furnishings, Equipment	(1) £1,787.05 (2) £1,787.05	N/A	N/A

	M&E Installation: Sanitary Appliances	(1) £3,141.50 (2) £3,141.50	N/A	N/A
	M&E Installation: Services Equipment	(1) £0 (2) £0	N/A	N/A
	M&E Installation: Disposal Installation	(1) £1,390.50 (2) £1,390.50	N/A	N/A
	M&E Installation: Water Installation	(1) £2,678.00 (2) £2,678.00	N/A	N/A
	M&E Installation: Heat Source	(1) £1,375.25 (2) £772.50	N/A	N/A
	M&E Installation: Space Heating and Air Conditioning	(1) £0 (2) £4,017.00	N/A	N/A
	M&E Installation: Ventilation Systems	(1) £6,397.06 (2) £1,081.50	N/A	N/A
	M&E Installation: Electrical Installations	(1) £4,140.60 (2) £4,140.60	N/A	N/A
	M&E Installation: Gas and Other Fuel Installations	(1) £309.00 (2) £309.00	N/A	N/A
	M&E Installation: Lift and Conveyor Installation	(1) £0 (2) £0	N/A	N/A

	M&E Installation: Fire and Lightening Protections	(1) £0 (2) £0	N/A	N/A
	M&E Installation: Communication, Security, Control System	(1) £257.50 (2) £257.50	N/A	N/A
	M&E Installation: Specialist Installations	(1) £0 (2) £0	N/A	N/A
	M&E Installation: Builder Work in Connection w/services	(1) £1,216.81 (2) £1,099.30	N/A	N/A
	M&E Installation: Testing and Commissioning of Services	(1) £393.79 (2) £355.76	N/A	N/A
	On Costs: Preliminaries (12%)	(1) £11,670.00 (2) £10,100.00	N/A	N/A
	On Costs: Overheads and Profit (6%)	(1) £6,530.00 (2) £5,660.00	N/A	N/A

Appendix 6: Perceived drivers for zero carbon homes (construction industry perceptions)

Theme	***Sub-Theme***
Legislative	Building Regulations
	Climate Change Act
	Planning
	Funding Requirements
	The Code for Sustainable Homes
Economic	Cost of Energy
	Market Demand
	Need for Affordable Homes
	Trailing
	Funding Requirements
	Prestige
	Incentives
	Energy Security
Social Responsibility	Fuel Poverty
	Moral Drivers
	Imperative to Act
	Sustainable Development
	Limited Resource Use
	Reduce Environmental Impact
Industry	Being seen to be green
	Fashion
	Housing Associations

Table populated with data from Heffernan, E. et al. (2015) ‘Zero carbon homes: Perceptions from the UK construction industry’, Energy Policy, 79, pp. 23–36. doi: 10.1016/j.enpol.2015.01.005.

Appendix 7: Perceived barriers for zero carbon homes (construction industry perceptions)

Theme	***Sub-Theme***
Economic	Capital Cost
	Scheme Viability
	Lack of Market Demand
	Perceived Risk
	Land Values
	Perceived Cost
	Home Valuations
	‘Green’ Overpricing
	Section 106/CIL
Skills and Knowledge	Knowledge – occupants
	Knowledge – build team
	Knowledge – design team
	Skills availability
	Public awareness
	Knowledge – maintenance team
	Knowledge – planners
	Fabric first
	Moving from demonstration to mainstream
	Awareness of workforce
	Poor competency
Industry	Availability of products
	Lack of collaborative working
	Unproven/Inappropriate technology
	Failing to be place specific
	Hard to persuade people
	Lack of drive from housebuilders
	Volume housebuilding

	Business models
	Resistance to change
	Design process
	Complexity
	Every project is a prototype
Legislative	Uncertainty re zero emissions heating policy
	Planning agenda
	Persuading government that sustainability will not stifle growth
	Moving the goalposts
	Current building regulations
Cultural	Housebuilding industry culture
	Householder culture
	Aesthetics culture

Table populated with data from Heffernan, E. et al. (2015) ‘Zero carbon homes: Perceptions from the UK construction industry’, Energy Policy, 79, pp. 23–36. doi: 10.1016/j.enpol.2015.01.005.

Appendix 8: Database of benchmarks and assumptions used within the cost analysis

Cost and technology Inputs

Input Items	Value	Units	Source	Notes/Assumption
General inputs				
Discount rate	3.50%		HMT The Green Book, 2018	from CCC analysis
Domestic Fabric Energy Efficiency Contribution Assumption	45%		Original data from Centre for Sustainable Energy - Towards Low-Carbon Housing Developments: a cumulative approach to reducing carbon emissions (March 2005) adjusted to modern standards as per and real consumption data from the Zero Carbon Hub[27] and metered data.	No accurate domestic thermal energy consumption data was available for modern building standards at time of analysis. Therefore, correction factors have been applied to past data sets (see source information). This is a constant throughout this analysis but in practice it would vary in accordance to location, design and climate.
Passivhaus	15	kWh/m2/yr	Passivhaus institute definition	
Passivhaus cost	119	£/m2	Passivhaus institute definition	The extra cost to upgrade to Passivhaus above the usual fabric cost, based upon data from The Passivhaus Trust (2019) 'Passivhaus Construction Costs'
Size correction for Scottish houses	20%		Assumed based on a comparison between real examples of new builds in Edinburgh vs England based benchmarks from Ramboll data and interview data	Bigger than in England
Lifetime of project	40	years	Assumed to show benefits of low fuel technologies	

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[27] https://www.zerocarbonhub.org/sites/default/files/resources/reports/Fabric_Energy_Efficiency_for_Zero_Carbon_Homes-A_Flexible_Performance_Standard_for_2016.pdf

Degree day area	2,398	days	https://www.eea.europa.eu/	North West Scotland
Number of flats in a block	20		Variable by scenario	
Number of blocks of flats	0		Calculated in model	
Flat block thermal diversification	0.8		Danish heat consumption curve in Heat Network code of practice	Lower peak thermal load due to differing thermal consumption behaviour between flats
Gas inputs				
Boiler CAPEX	60	£/kW	Based on information from previous energy projects	Installed cost
Heat cylinder	£ 1,000		Spons Mechanical and Electrical Services Price Book	
Cost of 1x0.45m radiator with installation	£ 100		Spons Mechanical and Electrical Services Price Book	
Heat cylinder for block of flats 4000L	£ 5,000		Spons Mechanical and Electrical Services Price Book	
Cost to connect to gas grid	£ -		Holding assumtion for Ricardo input	
Uplift cost	30%		Based on information from previous energy projects	Builders work in connection Testing and commissioning Consultancy fees Design costs Contractors costs Client's PM and legal costs Contingency Prelimins
Lifetime of boiler	20	years	CIBSE Guide M Supplementary Guidance 2020	
Boiler efficiency	85%		Based on information from previous energy projects	
Gas maintanence	4%		Variable, based on past experience and verified from interviews	
ASHP inputs				
ASHP CAPEX/kW	£ 700		Spons Mechanical and Electrical Services Price Book	Installed cost
Cost of 1.6x0.6m radiator with installation	£ 300		Spons Mechanical and Electrical Services Price Book	
Connection to grid	£ -		Holding assumtion for Ricardo input	
Heat cylinder 180L	£ 1,000		Based on information from previous energy projects	

Heat cylinder for block of flats 4000L	£ 5,000		Spons Mechanical and Electrical Services Price Book	
Uplift	50%		Based on information from previous energy projects	Builders work in connection Testing and commissioning Consultancy fees Design costs Contractors costs Client's PM and legal costs Contingency Prelimins
ASHP maintanence	£100		Based on interviews	
Lifetime of ASHP	15		CIBSE Guide M Supplementary Guidance 2020	
COP of ASHP	2.50		https://www.ofgem.gov.uk/sites/default/files/docs/drhi_factsheet_erp_for_installers_v2_0_mar_2016_web.pdf	Minimum cop for RHI funding
GSHP inputs				
GSHP unit CAPEX	1,800	£/kW	Spons Mechanical and Electrical Services Price Book, confirmed by interview	Installed cost
Cost of 1.6x0.6m radiator with installation	£ 300		Spons Mechanical and Electrical Services Price Book	
Heat cylinder 180L	£ 1,000		Spons Mechanical and Electrical Services Price Book	
Heat cylinder for block of flats 4000L	£ 5,000		Spons Mechanical and Electrical Services Price Book	
Connection to grid	-		Holding assumtion for Ricardo input	
Uplift	50%		Based on information from previous energy projects	Builders work in connection Testing and commissioning Consultancy fees Design costs Contractors costs Client's PM and legal costs Contingency Prelimins
GSHP maintanence	£100		Based on interviews	
COP of GSHP	3.00		Interviews	https://www.kensaheatpumps.com/what-is-the-efficiency-of-a-heat-
Lifetime of GSHP	15	years	Interviews	
Electrical wet option				
Electrical boiler CAPEX £/kW	£ 40	£/kW	Based on information from previous energy projects	Installed cost
PCM storage CAPEX	£ 1,600		Interviews	

Heat cylinder for block of flats 4000L	£ 5,000		Spons Mechanical and Electrical Services Price Book	
Connection to grid	£ -		Holding assumtion for Ricardo input	
Uplift	50%		Based on information from previous energy projects	Builders work in connection Testing and commissioning Consultancy fees Design costs Contractors costs Client's PM and legal costs ContingencyPrelimins
Cost of 1x0.45m radiator with installation	£ 115		Spons Mechanical and Electrical Services Price Book	
Electrical maintanence	1%		Broad assumpation based on intervews explaining that maintanance is low (assumed 1% of generation capex)	
Electrical boiler efficiency	90%		Based on information from previous energy projects	
Lifetime of wet electric system	20	years	Based on information from previous energy projects	
Electrical dry option				
Electric heater CAPEX £/kW	£ 400		Based on information from previous energy projects	Installed cost
Connection to grid	£ -		Holding assumtion for Ricardo input	
Uplift	25%		Based on information from previous energy projects	Builders work in connection Testing and commissioning Consultancy fees Design costs Contractors costs Client's PM and legal costs ContingencyPrelimins
Electrical maintanence	1%		Broad assumpation based on intervews explaining that maintanance is low (assumed 1% of generation capex)	
Electrical lifetime	20	Years	Based on information from previous energy projects	
Electrical radiator efficiency	100%		https://www.dimplex.co.uk/sites/default/files/assets//Dimplex%20Quantum%20Spec%20Sheet%20Issue%207.pdf	
District heating option				
Electric boilers CAPEX	£40		Based on information from previous energy projects	Installed cost
GSHP CAPEX	£1,800		Spons Mechanical and Electrical Services Price Book	Installed cost
Direct Electric share	20%		Sized to deliver thermal energy during peak demand	
Heat pump share	80%		Based on typical demand curve to maximise constant use	

Heat Pump Running Hours	5,000	hours	Based on information from previous energy projects	
Heat pump total capacity	-			
Electric Boiler Capacity	-			
SCOP of Centralised HP	3.5		Based on interviews	
Electric Boiler Efficiency	90%		Based on information from previous energy projects	
Maintanence (% CAPEX)	3.00%		Broad assumpation based on intervews explaining that maintanance is low (assumed 1% of generation capex)	
Energy Centre Cost	250	£/kW	Based on information from previous energy projects	
Uplifts	50%		Based on information from previous energy projects	Builders work in connection Testing and commissioning Consultancy fees Design costs Contractors costs Client's PM and legal costs ContingencyPrelimins
Network Cost (series 2)	900	£/m	Logstor quotes, based on the expected spine diameter based on the total peak and the diversification of 75% to meet the accepted pressure drop across the pipe	
HIU Cost	1,200	£	Quotes from other projects	
Substation Cost	90	£/kW	Quotes from other projects	
Distance between each building	12	m	Assumed for large buildings in inner city areas	
Length of branches (% of spine)	25%		no gardens or driveways	
Lifetime of equipment	20	years	Based on information from previous energy projects	
Connections per street	10		Assume all on one street	
Length between streets	20	m	Based on average suburban street pattern	
Number of streets	24			
Total connections	240			
Diversification	75%		Heat network code of practice	
Photovoltaic inputs				
Photovoltaic CAPEX £/m2	200	£/m2	https://www.greenmatch.co.uk/blog/2014/08/what-is-the-installation-cost-for-solar-panels	confirmed from experience

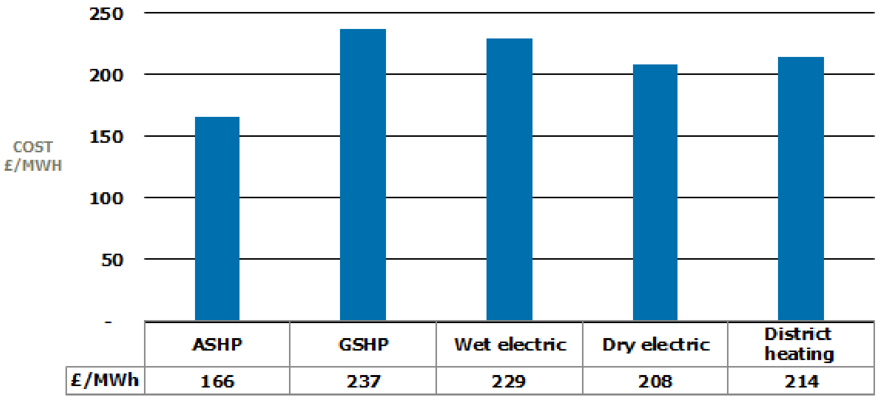
Maintanence (% CAPEX)	1%		Broad assumpation based on intervews explaining that maintanance is low (assumed 1% of generation capex)
Lifetime of equipment	30	years	Based on information from previous energy projects

Other General Assumptions

1. 5 bed houses heat consumption bigger than four bed than the difference between a 3 bed and a four bed
2. Each single technology option assumes that all heat demand is supplied by one heat source
3. Assume that pipe diameter DN 150mm will be used for district heating, might be slightly bigger than required but allow future development
4. Residential district heating energy centres have a diversification of 0.75
5. Assume REPEX is for heat source only
6. Assume that non-residential buildings have 1 emitter per 20m2
7. Spacing of houses for district heating option created assuming that (input number) houses are on each street, with half either side of the road. These streets have a spacing (inputs) leading to a cost for the spine.
8. Each block of flats is assumed to have a centralised heat source and thermal store except the dry electric option
9. Pipe cost assumes 1.5m pipe/m2 building area
10. The cashflow model assumes that there is no phasing of the project
11. REPEX is assumed to be distributed over the lifetime of the project rather than in chunks at end of life
12. Houses and non-residential buildings have their own heat source, flats have communal heat source
13. Assume that GSHP is installed in an average geological location, sensitivity analysis covers the possibility of dig being harder

Appendix 9: Detailed scenario results

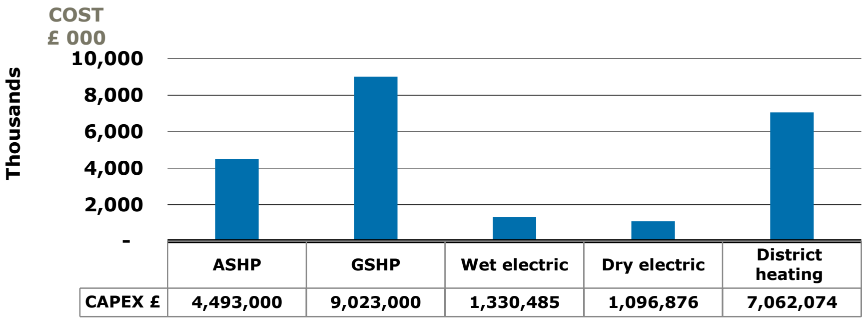
Scenario 1: Private housing development – detailed cost analysis results



£/MWh	ASHP	GSHP	Wet electric	Dry electric	District heating
£/MWh	166	237	229	208	214

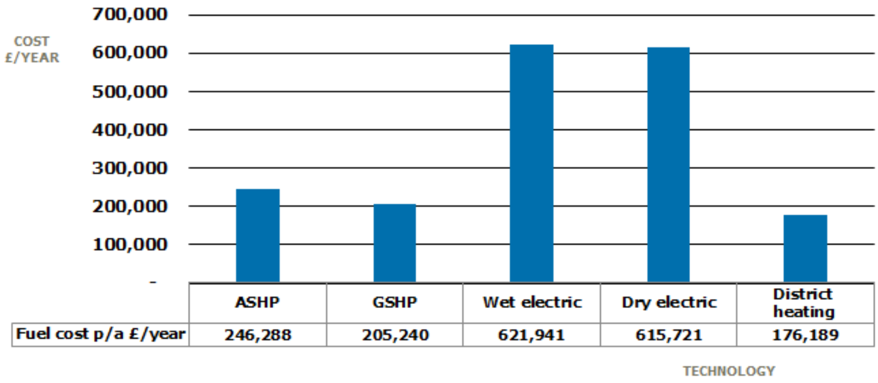
Levelised lifetime cost by technology option for Scenario 1

ASHP is the lowest-cost option on a lifetime basis in Scenario 1 from a lifetime cost perspective. This is due to a good balance of CAPEX and OPEX, giving a medium investment given the low density of heat consumption.



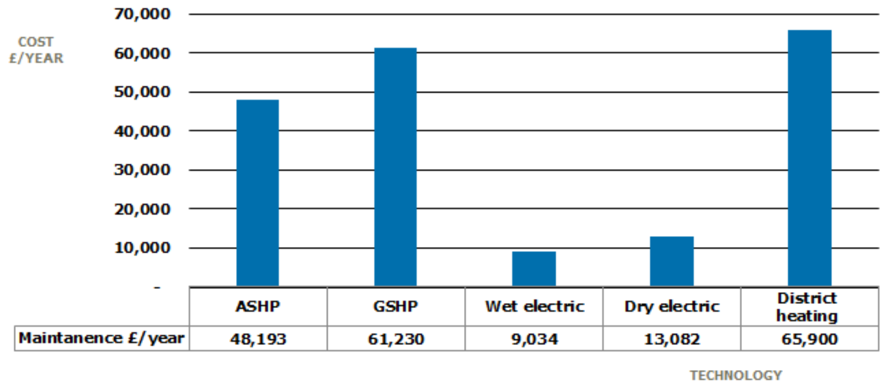
	ASHP	GSHP	Wet electric	Dry electric	District heating
CAPEX £	4,493,000	9,023,000	1,330,485	1,096,876	7,062,074

CAPEX cost by technology option for Scenario 1



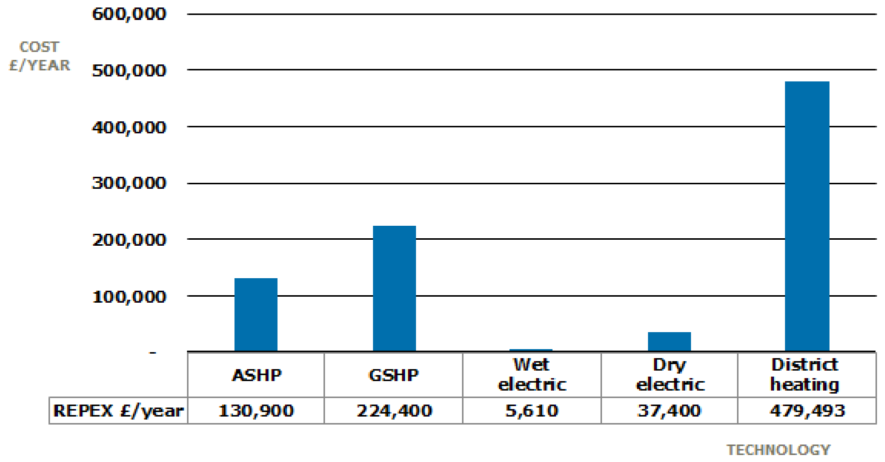
	ASHP	GSHP	Wet electric	Dry electric	District heating
Fuel cost p/a £/year	246,288	205,240	621,941	615,721	176,189

Annual Fuel cost by technology option for Scenario 1



	ASHP	GSHP	Wet electric	Dry electric	District heating
Maintanence £/year	48,193	61,230	9,034	13,082	65,900

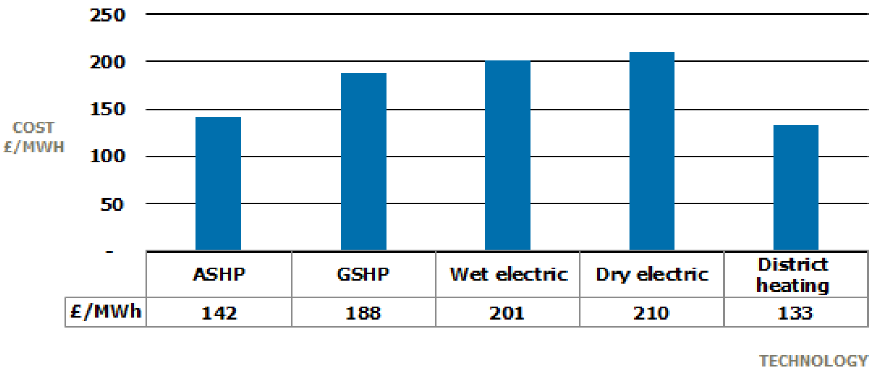
Annual Maintenance cost by technology option for Scenario 1



	ASHP	GSHP	Wet electric	Dry electric	District heating
REPEX £/year	130,900	224,400	5,610	37,400	479,493

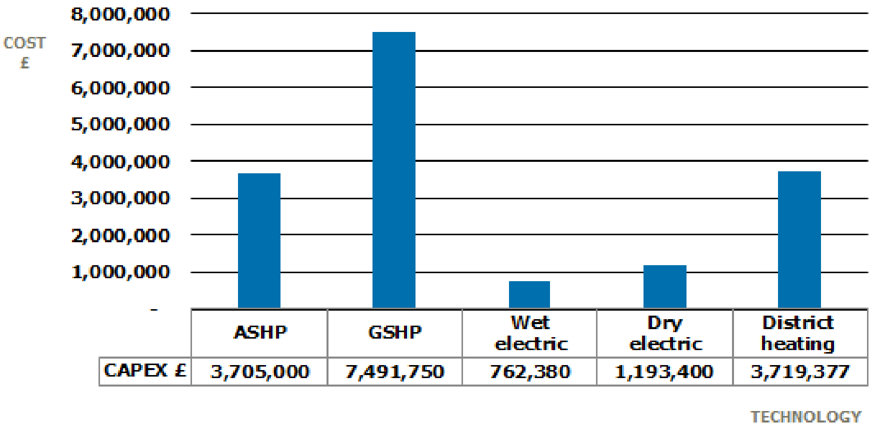
Annual Repex cost by technology option for Scenario 1

Scenario 2: Mixed-use development – detailed cost analysis results

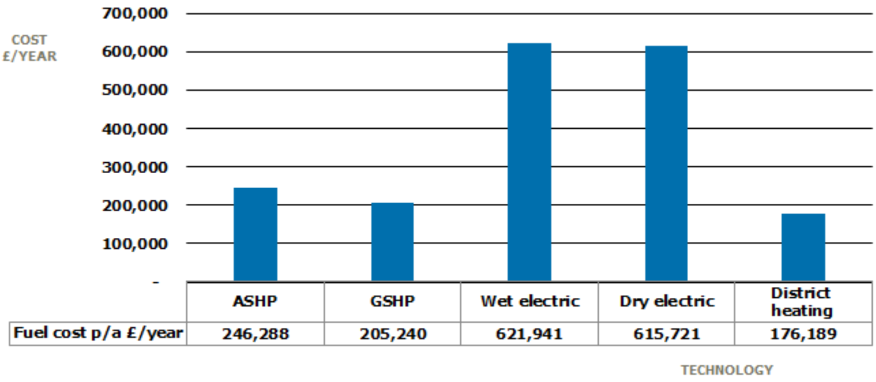


Levelised lifetime cost by technology option for Scenario 2

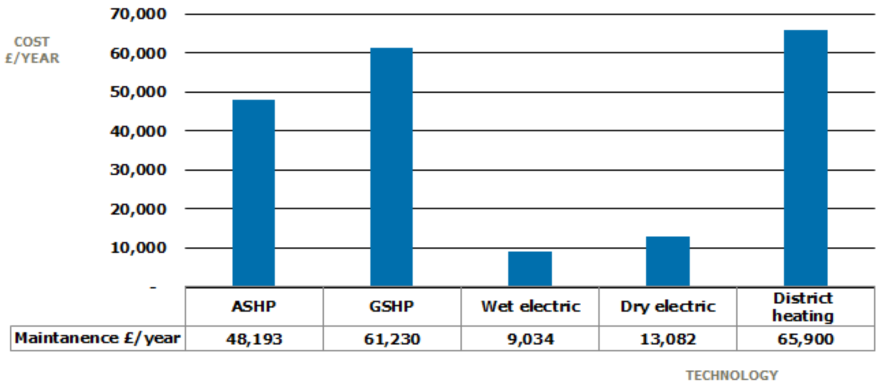
The district heating option is best for Scenario 2 as the energy demand is of a high density. We can assume that not all connections require their peak heat at the same time, so the system can be sized for a lower total peak, while much equipment is communal, reducing costs.



CAPEX cost by technology option for Scenario 2

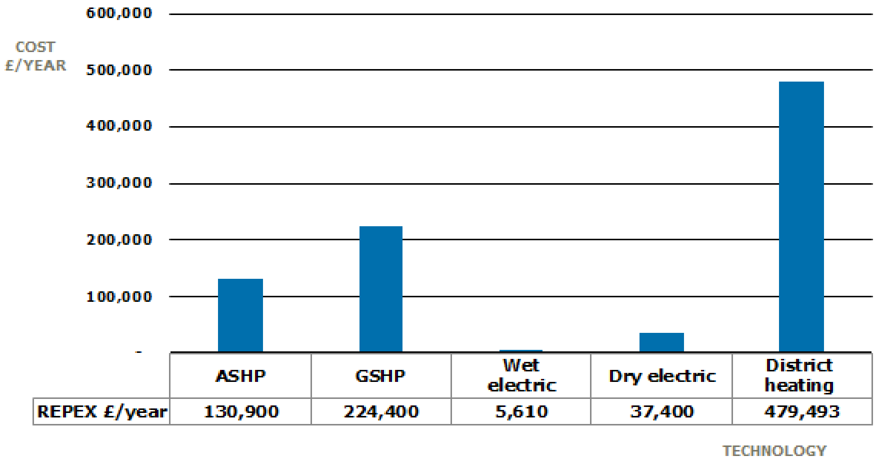


Annual Fuel cost by technology option for Scenario 2



	ASHP	GSHP	Wet electric	Dry electric	District heating
Maintanence £/year	48,193	61,230	9,034	13,082	65,900

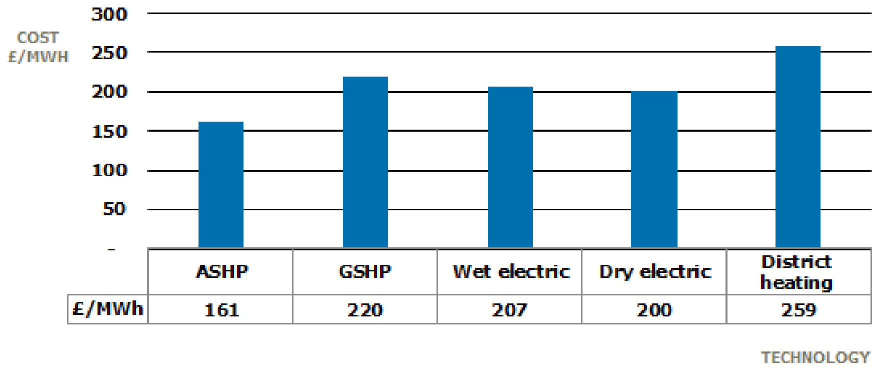
Annual Maintenance cost by technology option for Scenario 2



	ASHP	GSHP	Wet electric	Dry electric	District heating
REPEX £/year	130,900	224,400	5,610	37,400	479,493

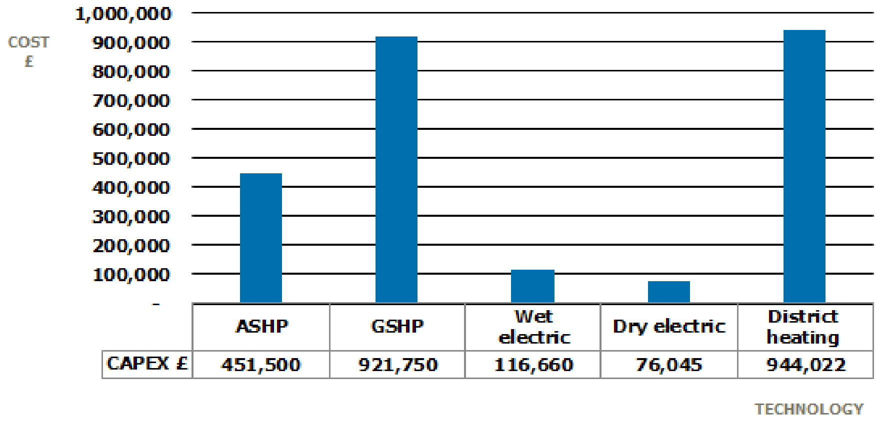
Annual Repex cost by technology option for Scenario 2

Scenario 3: Social housing development – detailed cost analysis results

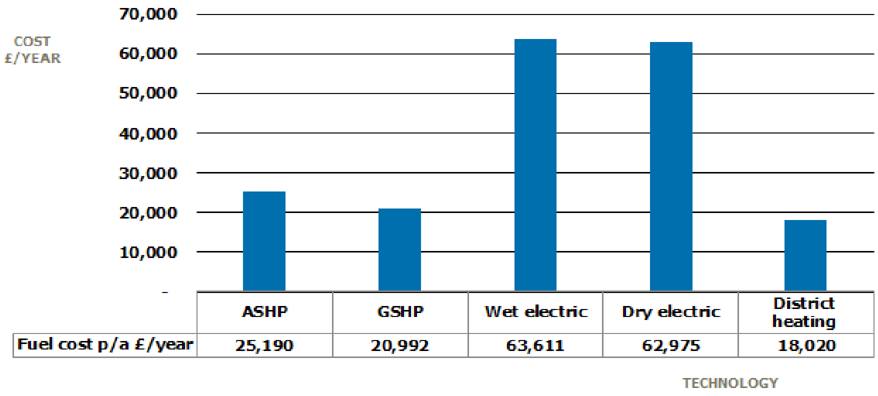


Levelised lifetime cost by technology option for Scenario 3

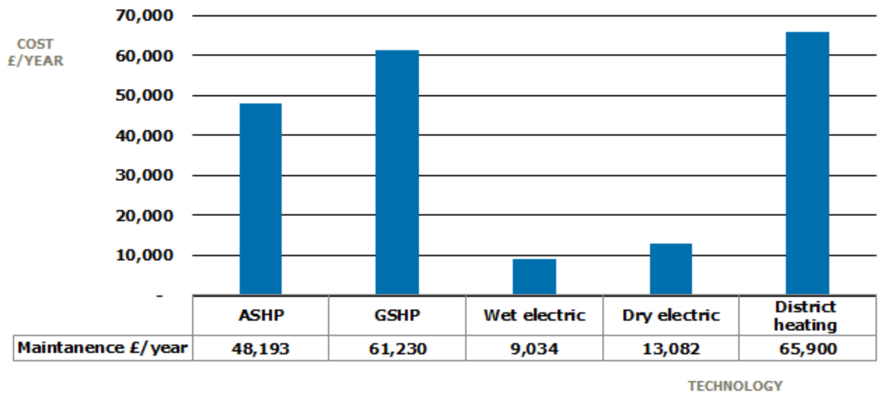
ASHP are the best option for Scenario 3 as they require a medium investment for solid return and are proficient in most factors. If the heat demand were smaller, dry electric would also be a viable choice.



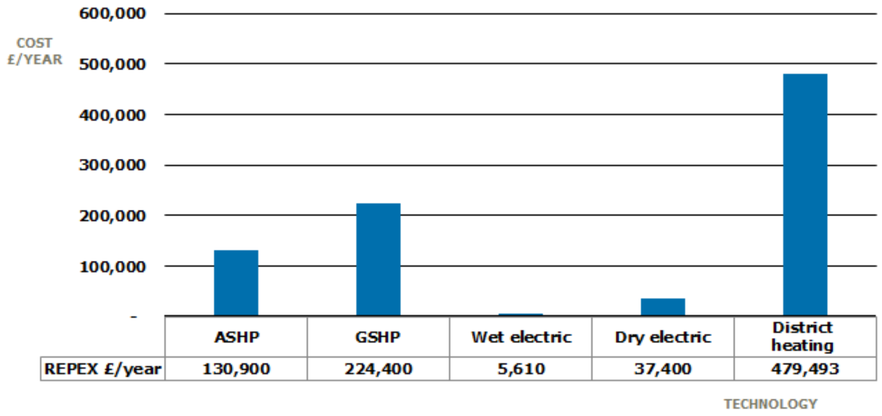
CAPEX cost by technology option for Scenario 3



Annual Fuel cost by technology option for Scenario 3

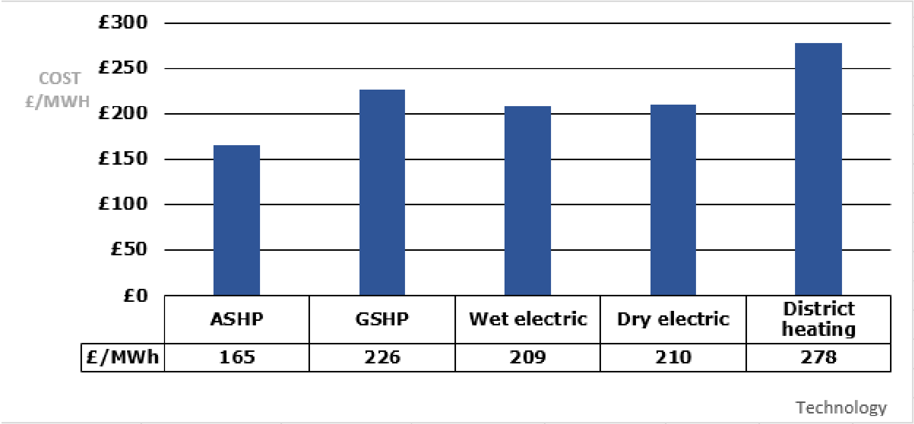


Annual Maintenance cost by technology option for Scenario 3



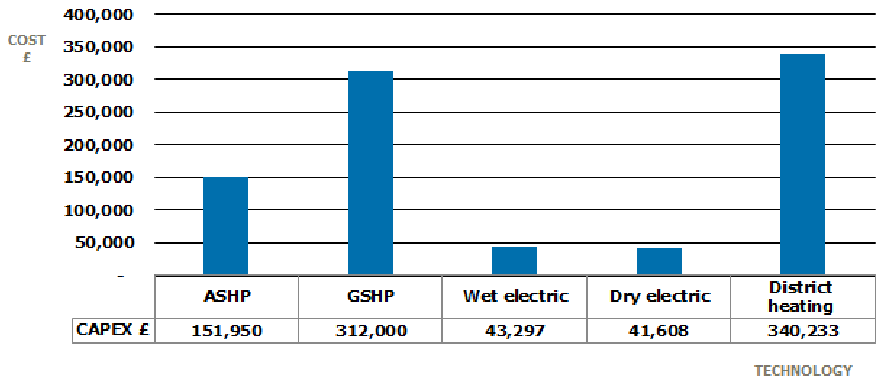
Annual Repex cost by technology option for Scenario 3

Scenario 4: Small-scale private development

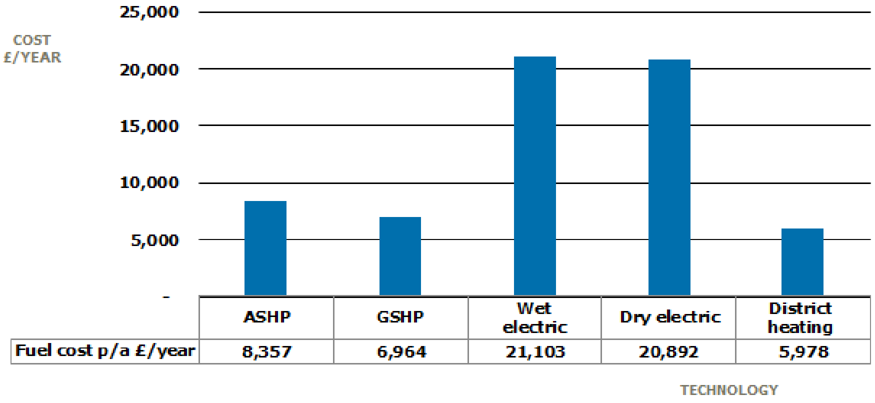


Levelised lifetime cost by technology option for Scenario 4

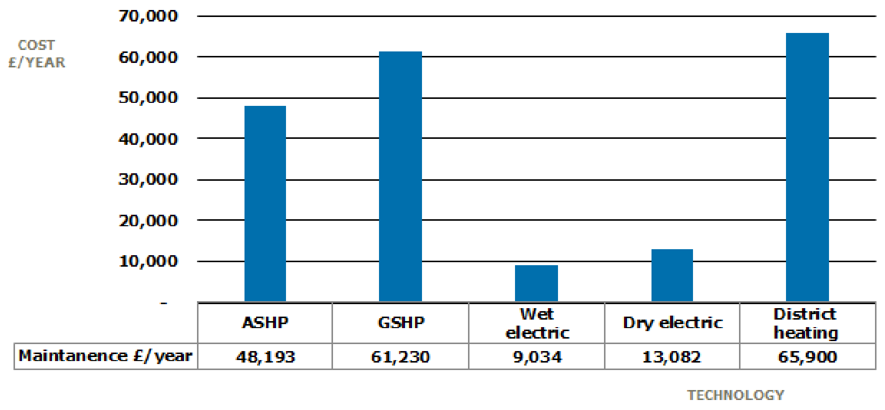
Scenario 4 shows that ASHP are the best option due to their solid performance over all factors. If the installation of GSHP were simple with no complications they would also be viable.



CAPEX cost by technology option for Scenario 4

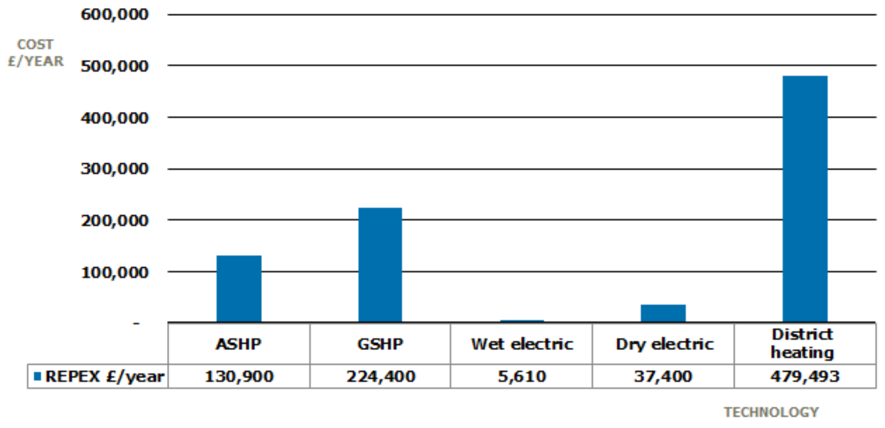


Annual Fuel cost by technology option for Scenario 4



	ASHP	GSHP	Wet electric	Dry electric	District heating
Maintanence £/year	48,193	61,230	9,034	13,082	65,900

Annual Maintenance cost by technology option for Scenario 4



	ASHP	GSHP	Wet electric	Dry electric	District heating
■ REPEX £/year	130,900	224,400	5,610	37,400	479,493

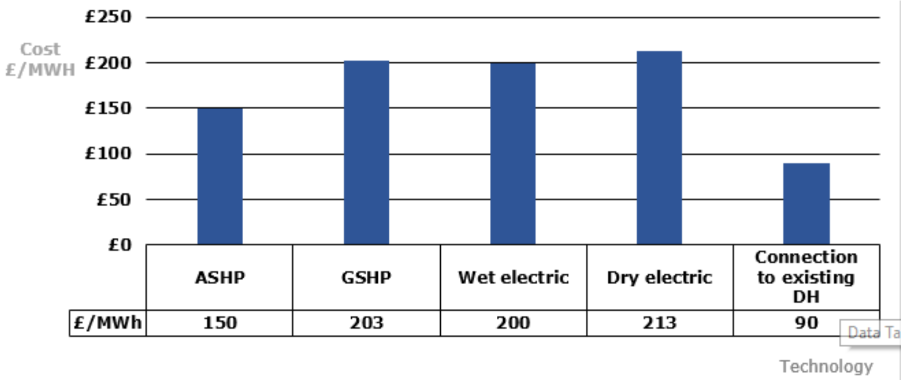
Annual Repex cost by technology option for Scenario 4

Scenario 5: Student accommodation

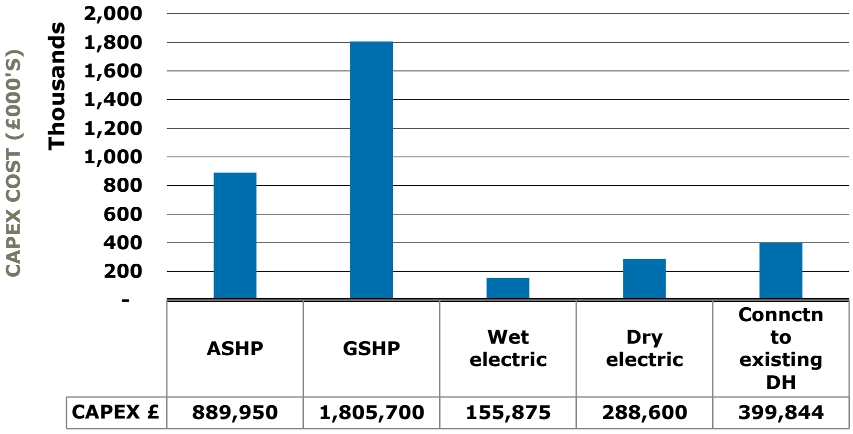
The following section presents the key results for each cost element calculated for Scenario 5: Student Accommodation, using the following scenario assumptions:

5. Student accommodation	A proxy is used for this scenario since appropriate benchmarks were not available for the building type and use. The scenario assumes: Apartments (3 bedrooms) – 111 units Which are intended to represent 6 single, en suite bedrooms, with shared kitchen and access to communal spaces in the buildings, connected through corridors

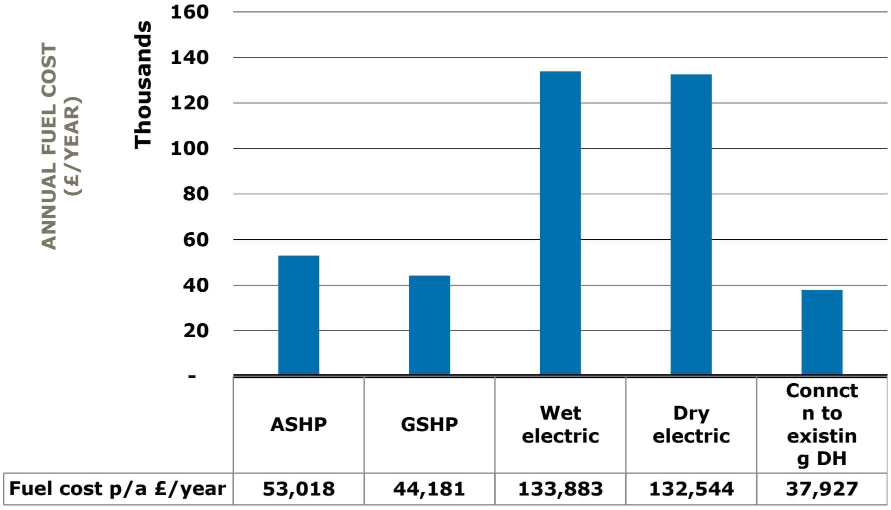
District heating is considered within this scenario as a connection into an existing district heating network, (assuming an additional length of 50m of pipework from the existing network, with a substation sized on the kW rating of connected building) since the scenario assumes a single building development.



Levelised lifetime cost by technology option for Scenario 5



CAPEX cost by technology option for Scenario 5

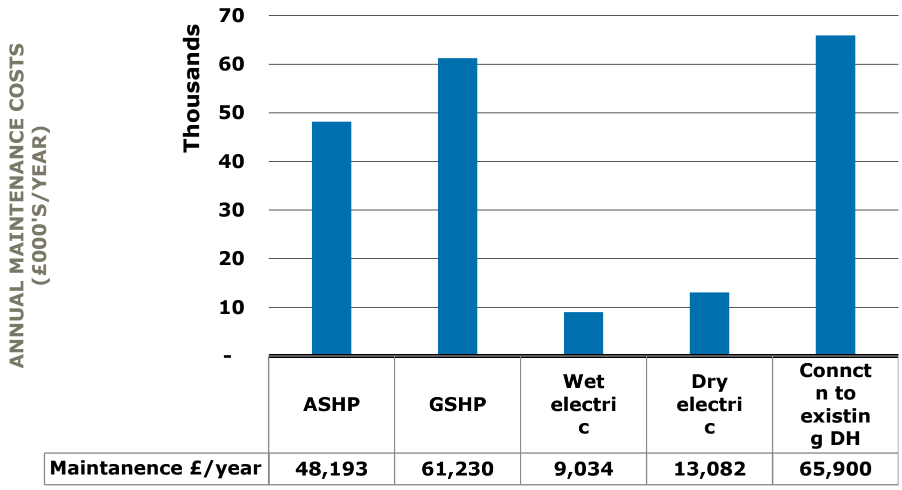


Annual Fuel cost by technology option for Scenario 5

Comments

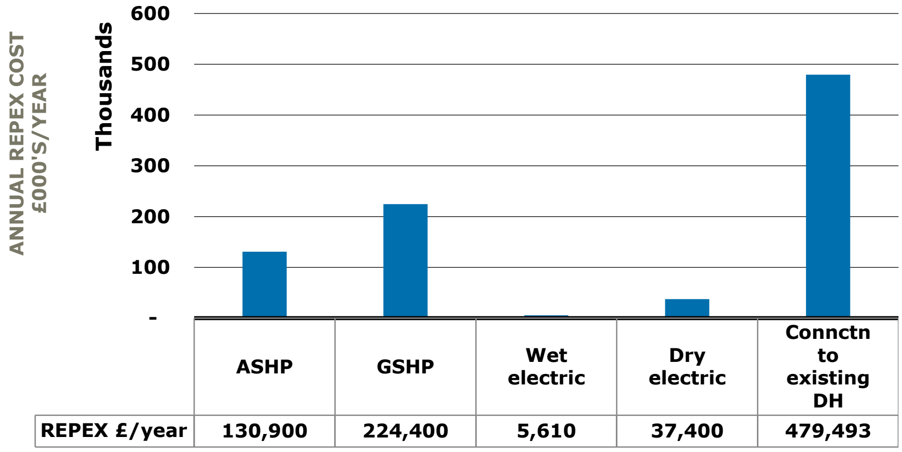
In this scenario, the student accommodation provider designs, builds and operates the building and heating system for its lifetime. The levelised lifetime cost is therefore a good basis for cost comparison across the scenarios, suggesting that connection to an existing heat network or an ASHP building solution would provide an optimum cost solution.

Other factors were also referenced as important by the stakeholder interviews, beyond cost. This included ease and speed of the technology control, and minimising space requirements. Bulk purchasing agreements were also possible for providers operating across the UK. This made dry electric options attractive as a technology solution in practice.



	ASHP	GSHP	Wet electric	Dry electric	Connctn to existing DH
Maintanence £/year	48,193	61,230	9,034	13,082	65,900

Annual Maintenance cost by technology option for Scenario 5



	ASHP	GSHP	Wet electric	Dry electric	Connctn to existing DH
REPEX £/year	130,900	224,400	5,610	37,400	479,493

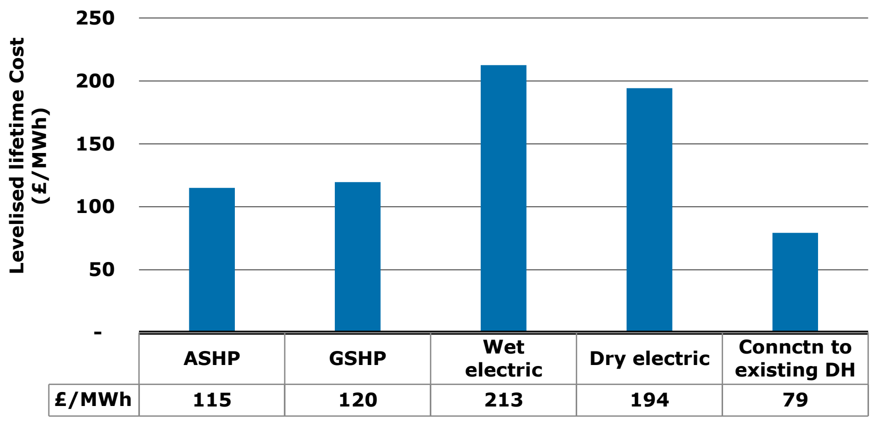
Annual Repex cost by technology option for Scenario 5

Scenario 6: Primary school

The following section presents the key results for each cost element calculated for Scenario 6: Primary school, using the following scenario assumptions:

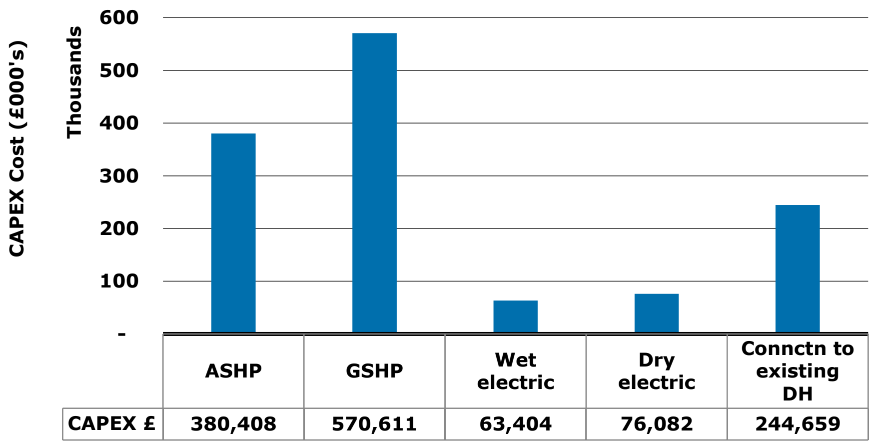
6. Primary school	Primary school building covering 5,300m^2

District heating is considered within this scenario as a connection into an existing district heating network, (assuming an additional length of 50m of pipework from the existing network, with a substation sized on the kW rating of connected building) since the scenario assumes a single building development.



	ASHP	GSHP	Wet electric	Dry electric	Conndtn to existing DH
£/MWh	115	120	213	194	79

Levelised lifetime cost by technology option for Scenario 6



	ASHP	GSHP	Wet electric	Dry electric	Connctn to existing DH
CAPEX £	380,408	570,611	63,404	76,082	244,659

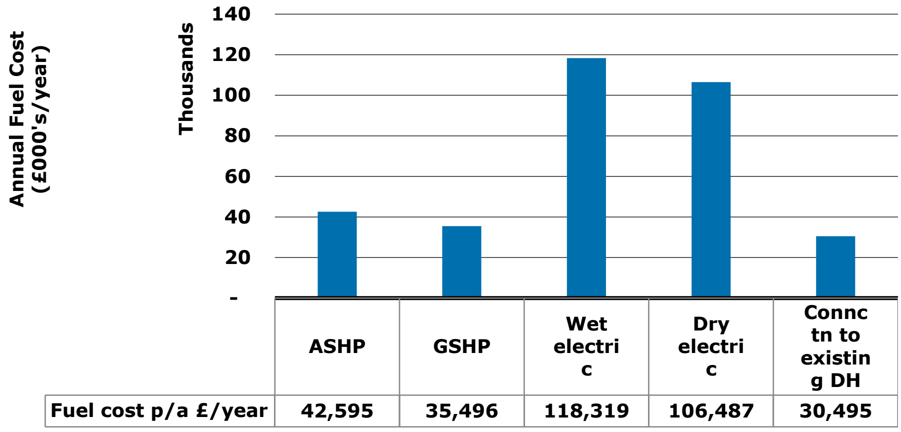
CAPEX cost by technology option for Scenario 6

Comments

In this scenario, the primary school is being designed, built and operated by the local authority. This makes the lifetime cost the most relevant cost comparison to consider for the purposes of minimising the cost of delivering zero emissions heating in the new build school.

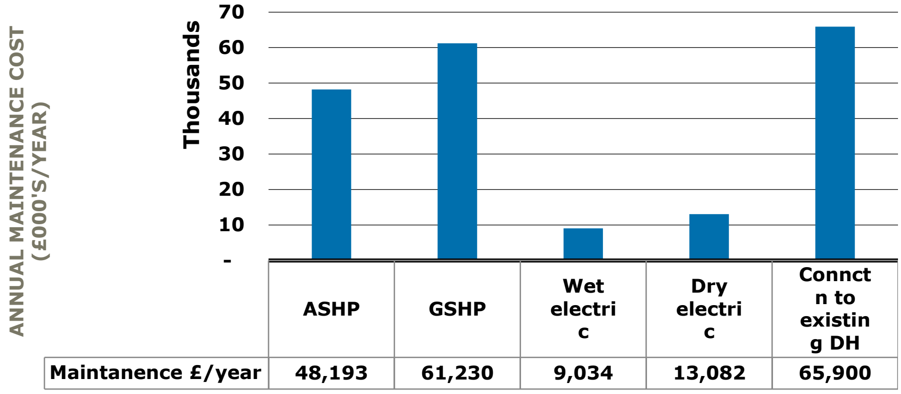
This analysis suggests that connection to an existing district heating network as the lowest cost solution, should there be one in the area. However, given that this scenario assumes the school is built as part of a house development, in a semi-rural area, this is unlikely to be the case.

Where connection to an existing district heating network is not possible, the



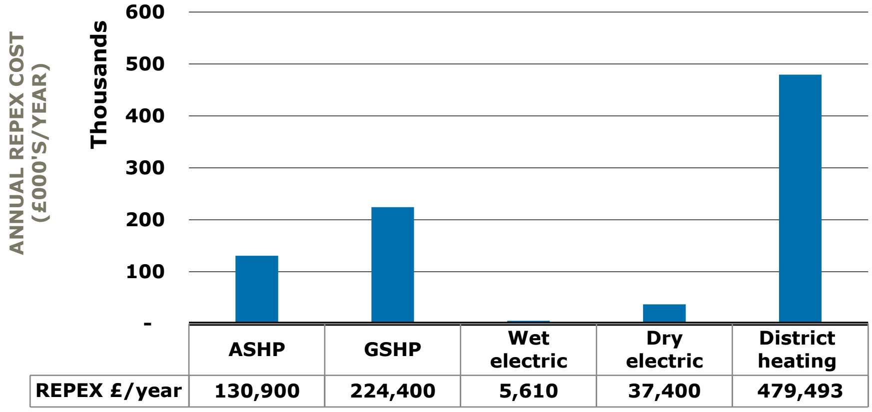
	ASHP	GSHP	Wet electric	Dry electric	Connctn to existing DH
Fuel cost p/a £/year	42,595	35,496	118,319	106,487	30,495

Annual Fuel cost by technology option for Scenario 6



	ASHP	GSHP	Wet electric	Dry electric	Connctn to existing DH
Maintanence £/year	48,193	61,230	9,034	13,082	65,900

Annual Maintenance cost by technology option for Scenario 6



	ASHP	GSHP	Wet electric	Dry electric	District heating
REPEX £/year	130,900	224,400	5,610	37,400	479,493

Annual Repex cost by technology option for Scenario 6

analysis suggests that ASHPs and GSHP would both be attractive options. The increased capital cost of a GSHP are offset by the lower annual fuel costs to meet the high heat demand profile of the school.

Although out of scope of this analysis, any grid constraints in the local area would also make a GSHP a good option given their higher COP and the resulting reduced peak demand on the electricity grid.

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