A report for the Committee on Climate Change

The costs and benefits of tighter standards for new buildings

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Contents

Appendices

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Executive summary

This study considers the potential opportunities for tightening building standards for new buildings to support the UK in meeting its legal obligations under the Climate Change Act. The study considers a range of tighter standards for selected housing and non-domestic buildings in tandem with a range for technologies for space heating and hot water; namely gas boilers, air source heat pumps (ASHP) and low-carbon heat networks (LCHN).

The study examines the 'social cost-effectiveness' of packages of fabric and low-carbon heating measures in new buildings. The cost-effectiveness of a package of measures to reduce emissions can be evaluated by its abatement cost. Expressed in £/tCO_2e, the abatement cost is the total lifetime cost of the package of measures divided by the associated total lifetime emissions savings.[1][2] A measure is considered cost-effective if its abatement cost is lower than the Government's target-consistent carbon values. Both central and high carbon values were used to assess the cost-effectiveness of tighter standards. These carbon values have been derived by the Government as estimates of costs consistent with international action to limit the expected increase in global temperature to 2°C above pre-industrial levels (and therefore consistent with an 80% reduction in UK emissions by 2050). For a tighter target, higher carbon values are likely to be appropriate[3]

Delivering each standard in a new building is also compared to achieving the same standards via retrofit of a building built to the current minimum regulatory requirement for England. This gives an indication of the implications of trying to improve performance via retrofit, if standards for new build are not changed.

Background

Minimum regulatory requirements relating to the energy and carbon performance of buildings have been largely unchanged in recent years. However, reviews of regulatory requirements are now underway or imminent across the UK and the Energy Performance of Buildings Directive (EPBD) provides a further stimulus for standards to be reassessed[4]. Recent years have also seen substantial changes in key factors influencing the carbon performance of buildings. For example, the carbon intensity of grid electricity has more than halved in the newly published (but not yet adopted) SAP10 method, in comparison to SAP 2012. CCC projections suggest the real carbon intensity of electricity will continue to fall, halving again to under 100g CO_2e per kWh by 2030. Also, the costs and performance of different technologies continue to evolve. Against this background, it is important that the appropriate scope and form of future standards is examined so that opportunities for cost-effective changes are not missed, and the need for expensive retrofit of new homes can be avoided.

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[1] The Government's carbon values for policy appraisal are designed to be consistent with action required under the Climate Change Act. The abatement cost of a package of measures is compared against the average discounted carbon value across the lifetime of the measures. For further information on the CCC's approach to assessing cost-effectiveness, see Committee on Climate Change (2015) *Sectoral Scenarios for the Fifth Carbon Budget – Technical report*, box 1.2.

[2] Based on the net present value of the differences in capital, maintenance and variable energy costs set against annual carbon savings over 60 years.

[3] In this context, it is important to note the recent request made by UK and devolved Governments for advice on the date by which the UK should achieve a net zero greenhouse gas or carbon target.

[4] Among other things, the EPBD requires that member states adopt Nearly Zero Energy Building standards for new buildings by 2019 (for public buildings) and 2021 (for other buildings). See: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32010L0031&from=EN

Government and industry have set a series of ambitious targets within the Clean Growth Buildings Mission and the Construction Sector Deal. These aim at delivering increased innovation and productivity and reduced whole life carbon emissions in the built environment.

This study does not quantitively include any medium to long term cost savings associated with productivity gains of the sort envisaged by the Construction Sector Deal. Should these savings be realised, then this would have the effect of reducing build costs and the additional costs of more energy efficient and lower-carbon buildings, making the achievement of tighter standards more cost-effective.

This analysis, alongside a programme of stakeholder engagement[5] and review of a variety of existing building standards and accreditation methods, has produced the findings and informed the associated recommendations set out in this report.

Key findings

- **1) The opportunity from low-carbon heat**
  - **Low-carbon heat supply is a priority** for delivering long term carbon savings. This is true of both new domestic and non-domestic buildings but is particularly important for homes and other naturally ventilated buildings. Using cost-effective low-carbon heat (via an ASHP), the regulated operational carbon emissions over 60 years of a home built in 2020 are more than 90% lower than an otherwise equivalent gas-heated home. Savings of nearly 80% were identified for a naturally ventilated office and of 30% for an air-conditioned office.
  - **Photovoltaics are not a substitute for low-carbon heat.** Equivalent lifetime savings in emissions cannot be achieved using onsite renewable energy generation (e.g. via photovoltaics) to compensate for the emissions from a gas boiler. The net carbon savings associated with this generation will decline as the grid decarbonises while the emissions associated with gas use are not projected to change materially. Further, the energy generation profile of photovoltaics (highest during summer days) does not well match typical heating demand profiles[6] (highest in winter evenings) giving rise to the need for storage, potentially inter-seasonal, which has its own costs and energy losses.
  - **Fabric efficiency is not a substitute for low-carbon heat.** In homes, the lifetime carbon savings achievable from the use of low-carbon heat are substantially greater than even the most energy efficient fabric standards when paired with a gas boiler[7] (see figure E.1). This is in part because of the ongoing use of gas to supply domestic hot water, which would become the most significant contributor to the building's carbon emissions as the space heating demand is reduced and the carbon associated with electricity declines.
  - **Low-carbon heat is cost-effective when built into new homes from 2021**. Low-carbon heating in the form of an ASHP[8] is cost-effective in all new homes built from

[5] Stakeholders consulted in the course of the study are detailed in the main report.
[6] Photovoltaics', when installed in a home supplied with low carbon heat, could provide a valuable additional benefit of reducing levels of additional energy demand from the grid. These benefits are greatest in homes with low space heating demand and when combined with heat / battery storage systems.
[7] The most energy efficient home specification was that with an annual space heating demand of under 15kWh/m^2.
[8] An ASHP has been used to illustrate onsite low-carbon heating sources. Other possible technologies include ground source heat pumps (GSHP) or even the use of solar technologies together with

2021, when compared against central carbon values. In housing, lifetime carbon savings of over 90% are achieved at a capital cost uplift of around 1-2%. Connecting to a LCHN may also be a cost-effective carbon reduction solution in situations where the heat density and scale enable efficient operations[9].

– **Low-carbon heat need not increase running costs**. If buildings perform as designed, and using CCC system efficiency values, low-carbon heat via an ASHP should reduce the running costs of a home built to the Part L notional specification, in comparison to an equivalent home with a gas boiler[10]. However, running costs of an ASHP could be higher if the system is poorly designed, installed or commissioned, or if the occupier does not use the system correctly. In ultra-high efficiency buildings, the risk of increased running costs is substantially reduced, with potential for annualised savings of around £85-100 per year for a semi-detached house[11].
– **The carbon penalty for delayed action is significant**. As figure E.1 shows, a semi-detached home built in 2020 with gas heating and retrofitted with an ASHP in 2030 can be expected to emit more than three times more (or 9-10 tonnes) carbon over 60 years than if the heat pump was installed when the house was built. If 300,000 homes are built annually by the mid-2020s, each year of delay in adopting lower-carbon heat technologies could result in several million tonnes of avoidable carbon emissions, even if the technology were to be retrofitted after only 10 years.

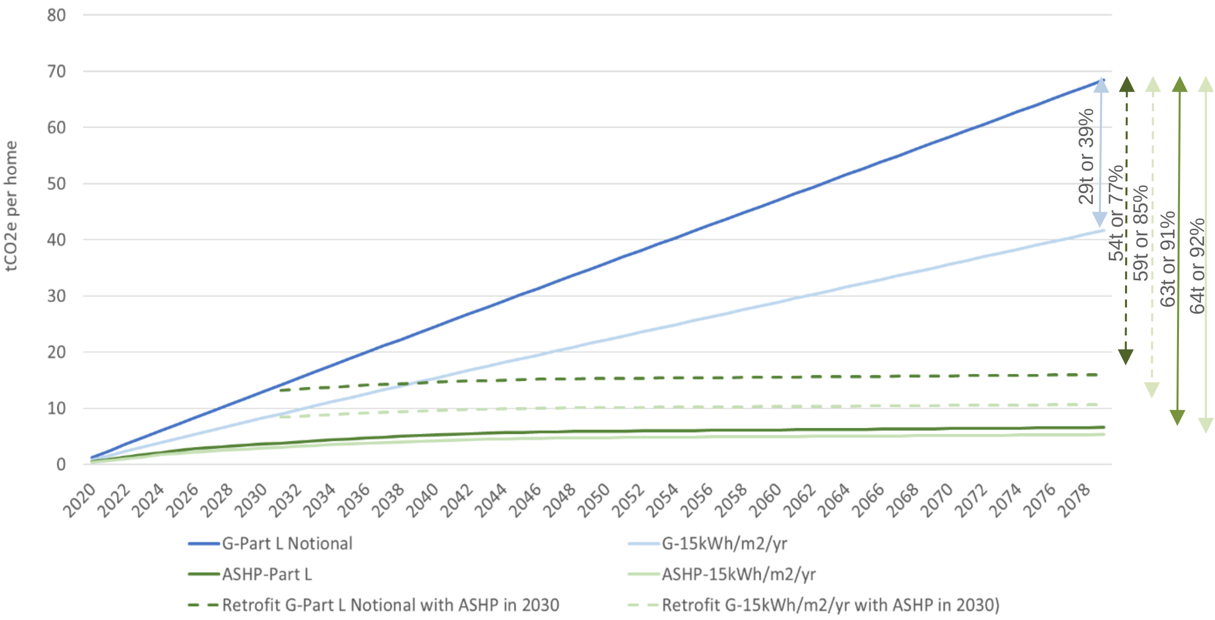
thermal or battery storage. Hydrogen has not been modelled here as a low-carbon heating option because it is assumed to would require conversion of the gas grid rather than being applicable to new homes as a bespoke solution. Hydrogen has been considered separately in CCC advice (see for example CCC (2018) *Hydrogen in a low-carbon economy*).

[9] The costs and cost-effectiveness of LCHN connections will vary considerably according to the development type and context. Results of the single LCHN scenario considered in this report, should therefore be taken as indicative only. This study prioritises consideration of ASHP as a more widely applicable low-carbon heat source.

[10] Unit energy costs are slightly higher until 2040, but the avoided gas standing charge results in an overall annual cost saving.

[11] Alongside a heat pump, ultra-high energy efficiency standards (representing a space heat demand of 15 kWh/m^2/yr) can deliver annualised savings of £87 for a semi-detached home built in 2020, and £98 for a semi-detached home built in 2025.

Figure E.1 Cumulative carbon emissions from a semi-detached house built to different space heating demand standards with either a gas boiler or ASHP, including retrofit of ASHP after 10 years[12]



- **2) Alongside low-carbon heat, ultra-high fabric efficiency standards offer opportunities for cost-effective savings across most house types by 2025**[13]
  - **Tighter fabric standards deliver a range of benefits**. While low-carbon heat delivers very substantial benefits, even at current efficiency levels, there are several material benefits from tightening fabric standards alongside the installation of low-carbon heat:
    - Further savings in running costs can be achieved (around £30-£40 relative to installing a heat pump alone),[14] while also improving the quality of the internal environment
    - Reduced energy consumption reduces the quantity of low-carbon energy required to meet UK demand

[12] The options being compared are homes built to either the Part L 2013 Notional Specification or to a specification with space heating demand of 15kWh/m^2/yr with heat provided by a gas boiler (G-) or air source heat pump (ASHP-).
[13] In this context ultra-high efficiency is a space heating demand of 15kWh/m^2/yr or less as modelled by SAP 2012. This is similar to a Passivhaus level of performance, notwithstanding the variations in the approach to modelling performance in the Passivhaus Planning Package and SAP.
[14] The scale and nature of the bill impact is in part a function of the standing charges associated with gas and electricity bills and will vary with the scale of standing charges assumed. Where moving to and from a tariff which does not include standing charges (i.e. where these costs are incorporated in the unit rate), the saving associated with ultra-high energy efficiency standards and a heat pump relative to installing a heat pump alone could be up to £40.

    - Lower heat losses help to reduce or avoid peaks in energy demand associated with space heating[15]
    - Potential for fewer radiators and reduced heating distribution system, freeing up internal wall space, saving associated capital and maintenance costs while also reducing the risk of water damage over the building's life.[16]

  - **Ultra-high energy efficiency standards, installed alongside an air source heat pump, represent a 1-4% uplift on build costs relative to a home built to current regulations.** Costs are highest for the least efficient building forms such as detached houses.
  - **Ultra-high efficiency housing is more cost-effective than making smaller improvements on current regulatory requirements.** Ultra-high levels of energy efficiency are generally found to be more cost-effective than tightening to 20-30 kWh/m^2/yr of space heat demand. This reflects a significant (up to c.£3,300) saving in the capital cost of the radiators and heating distribution system which helps offset some of the additional costs associated with the most energy efficient fabric specifications.
  - **Where MVHR is used it should be paired with efforts to achieve very high levels of airtightness.** The use of MVHR in homes without high levels of airtightness (i.e. 2.0 m^2/m^3/hr or below) could result in additional running costs because the costs of operating the fans outweigh the savings in reduced energy consumption.
  - **Tighter energy performance should be accompanied by other related standards.** Stakeholder engagement highlighted the importance of ensuring that, alongside any transition to ultra-high efficiency standards, standards and policy frameworks effectively manage overheating risks, ensure adequate ventilation and support easy maintenance of key building systems.
  - **A phased transition to tighter housing standards**. An ultra-high efficiency specification for homes requires high levels of airtightness together with high performance windows and mechanical ventilation. These systems will require changes to established practices and the learning of new skills, especially if these changes are paired with a change to a low-carbon heating system. A phased, but concise, transition process would therefore be appropriate to enable the industry to prepare, innovate and test accordingly. This could be supported by facilitating or providing incentives for those wishing to move ahead of the regulatory trajectory.
  - **Active support for the transition is important**. The transition should be supported by suitable investment in tools, guidance, training and quality assurance processes that are commensurate with the challenge and scale of the opportunity.

- **3) There is potential to cost-effectively tighten standards for new non-domestic buildings.**

  - **Non-domestic buildings are diverse with widely varying levels of energy demand.** Due to scope limitations, the analysis in this study considers only two archetypes: a naturally ventilated and an air-conditioned office. The results are

[15] This is an area that would benefit from further research and consideration in standard setting. Currently SAP and SBEM energy models do not consider the scale and dynamics of peaks in energy demand, so the associated external costs on the energy system are not being fully captured.
[16] Examples of recent Passivhaus or similar ultra-efficient homes suggest that radiator numbers can be reduced from c.10-12 to 3-4 centrally located panels in a semi-detached house. Although not tested in this study, it may be possible for ultra-energy efficient homes to avoid wet heating systems altogether and rely only on direct electric heating via ventilation and a limited number of panel heaters.

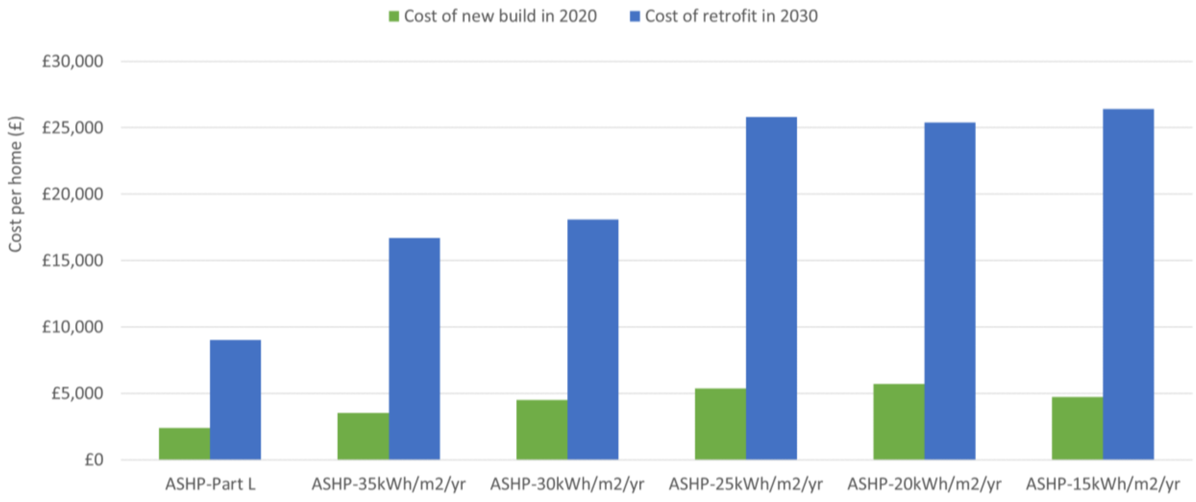
therefore indicative only, and further work is needed to assess the opportunities and costs for other building types and designs.

- **The greatest carbon savings are from low-carbon heat, but energy efficiency reduces running costs**. For the assessed offices, the greatest potential carbon savings arise from the use of low-carbon heat, while energy savings, primarily through lighting and building services efficiencies, can deliver significant savings in running costs alongside this.
- **Reduced carbon emissions are cost effective in 2020.** A 15% reduction in carbon emissions compared to Part L is cost-effective against central carbon values in 2020 with savings of 20-25% cost-effective by 2020 or 2025 depending on the heating system and archetype.
- **Low-carbon heat is cost-effective by 2025 or earlier when installed alongside energy efficiency measures.** Analysis suggests that low-carbon heat via ASHPs will be cost-effective in comparison to a high carbon value by around 2025. When combined with simple energy efficiency measures, such as high efficiency lighting, low-carbon heat is cost-effective in 2020 against a high carbon value and by 2025 against a central carbon value.

- **4) Achieving higher standards via retrofit is very expensive compared to designing them into new buildings from the outset**

  - **Costs of achieving higher standards via retrofit are three to five times higher than for new buildings**. The costs of installing low-carbon heat as a retrofit to an existing gas heated semi-detached home is around £9,000, over three times the cost than if installed in a new build. To improve fabric standards and install low-carbon heat via retrofit, costs range from over £16,000 to more than £25,000 per home - up to five times the costs of achieving the same standards in when first constructing the home (see figure E.2). For non-domestic buildings, achieving higher standards via retrofit is between approximately 3 and 10 times the costs of delivering them in the new building.

Figure E.2 Additional cost of installing ASHP and meeting space heating standards in a new semi-detached house or via retrofit[17]



[17] Both costs are in nominal 2018 prices, i.e. the undiscounted cost in the year the work is undertaken.

- **Targeted preparatory measures in new buildings can significantly reduce retrofit costs**. The installation of radiators and hot water stores (where used) that are compatible with low temperature heating can reduce the costs of retrofitting an ASHP by £1,500-£5,500[18], depending on house type, at a capital cost of £150-£500 per home. Low temperature radiators will also provide a small improvement in the efficiency of a gas boiler prior to the retrofit of the ASHP (assumed to be around 3%).

- **5) Managing the performance gap is an important first step**
  - **'As built[19]' performance is more important for low-carbon heat.** The introduction of low carbon / low temperature heating systems increases the importance of systems performing as intended to deliver the affordable comfort. This is because if a building's heat losses are substantially higher than estimated there will be a risk of the heating system being run at higher operating temperatures to meet the additional demand. This would result in substantial increases in energy use, to replace the additional heat losses, and because the system is less efficient at higher temperatures. With traditional (gas) heating the efficiency losses associated with higher than expected heat losses is far smaller.
  - **Understanding the performance gap to help close or manage it**. A gap between design and as built performance has been identified for both housing[20] and non-domestic buildings[21]. Further work to gather information on the real in use performance of new buildings will help to better understand the scale and nature of the performance gap and assist in identifying the steps to close it so that users can have more confidence in the performance of new buildings.

- **6) Compliance tools and methods must change**
  - **Current compliance tools (SAP and SBEM) provide a poor method for estimating operational carbon emissions.** Use of static emissions factors and failure to update them for over five years means that currently used tools significantly overestimate the carbon savings from use of Combined Heat and Power (CHP) or photovoltaic (PV) panels and underestimate the savings from use of heat pumps or mechanical heat recovery systems.
  - **Key assumptions need to be revised to accurately value the benefits of low-carbon technologies.** The new SAP 10 compliance method includes a significant number of methodological changes[22] , including updating the significantly out of date

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[18] For a semi-detached house, the nominal cost of retrofitting an ASHP into a Part L 2013 compliant home in 2030 is around £9,000 in 2018 prices. This includes for the heat pump and sundries, a hot water cylinder and new radiators with associated adjustments to pipework. If the home were 'low temperature ready' the cost would be c.£6,300, a saving of £2,700 due to the ability to retain existing radiators and pipework.

[19] i.e. The performance of the home when completed under a defined operating regime. 'As built' performance is distinct from 'design' performance in that it reflects the performance of the actual completed home and from 'operational' performance in that it does not include the impact of occupancy patterns and behaviour.

[20] Zero Carbon Hub, 2014.Closing the gap between design & as-built performance: End of term report

[21] InnovateUK , 2016. Building Performance Evaluation programme: Findings from Non-domestic buildings.

[22] Among a wide range of potentially substantial changes to the modelling method are amendments to assumptions about heating pattern and the efficiency of different systems. The full implications of these changes will not be apparent until compliant modelling software is available, but it appears likely that some will act to reduce predicted energy consumption (e.g. changes to heating pattern) while others may increase energy use for some designs (e.g. system efficiencies and losses).

carbon emission factor for electricity used within SAP 2012 and incorporating new approaches to estimating hot water use and lighting energy. However, the new standard still maintains a focus on presenting the static emission factors for each fuel that represent their short-term average carbon intensity and do not incorporate the government's projections for long-term reductions in carbon intensity of electricity. As a result, even the revised method will still substantially overestimate the expected lifetime carbon emissions from electricity use. CCC expectations for the efficiency of heat pumps are also substantially different from those used within compliance methodologies and it is recommended that the evidence for updating assumed efficiency levels is reviewed. Finally, SAP can have a material influence on technology uptake through the technologies it includes and excludes from the methodology – currently whilst technologies such as solar PV are incorporated, technologies such as solar thermal are not yet fully valued (for instance, SAP does not allow for solar thermal to contribute to space heating needs). Recent investment in the methodologies underpinning standards has been very limited, when viewed as a proportion of the value of the economic output they influence.[23] Investment in these methodologies should be proportionate with their impact.

- **Compliance tools and requirements should consider a wider range of factors.** Current compliance tools do not adequately consider some key factors that will be critical to ensuring new homes support the delivery of a low-carbon energy system for all of the UK. These considerations include estimating the peak demand for energy associated with new homes, accounting for the synchronicity of energy generation and demand. There are precedents within international building standards such as Passivhaus for methods that could be used to address these factors.
- **There is a case for adopting absolute performance targets.** Especially for peak demand. Such an approach would reward the use of energy efficient designs, ensuring that the least efficient building forms must work harder to minimise their energy use, reducing the associated impacts on running costs and potential for higher peak demand.

Areas for further investigation

The potential of hot water efficiency measures and other solutions to provide cost-effective carbon and energy savings should be investigated as part of the development of future standards. This future analysis should use modelling tools that address the considerations described previously, i.e. to ensure they appropriately value the carbon emissions from use of different fuels, incorporate the most up-to-date knowledge on system efficiencies and usage, and consider the effects of building design and specification on levels of peak as well as total demand.

[23] For instance, BEIS's 2017 'Invitation to Tender for technical services to maintain methodologies for calculating energy performance of buildings' invited tenders for development of SAP within a budget of up to £675,000 per annum (excluding VAT). This compares to an annual economic output of housebuilding of £38bn in England and Wales in 2017 according to the House Builders Federation. See House Builders Federation and Lichfields (2018) The economic footprint of House Building in England and Wales.

Actions and route map

Below we set out a potential route map for tightening new build standards, based on the research undertaken as part of this study. Given the parallel expectations for a substantial increase in housing delivery over the first part of the 2020s, a phased approach can help ensure that the industry has enough time to prepare for changes, and learn the associated lessons, before pursuing further changes.

The first step should be the establishment of the necessary tools to support standard development and project decisions. Future standards should drive a transition to low-carbon heat and, together with a phased and cost-effective tightening of energy efficiency, reduce running costs and minimise the demands placed on electricity generation and supply infrastructure.

1 – A robust platform and ongoing active support programme – 2019 onwards

The scale of the changes required to deliver both low-carbon heat and tighter performance standards should not be underestimated. It is essential that sufficient investment is available to provide necessary tools and support industry change.

Government and industry should work together to provide a robust basis for delivering a transition to low-carbon heat and progressively higher levels of efficiency in new buildings. Key steps would include:

- Agreeing a route map and action plan to drive change and support the industry in delivering high quality, low-carbon, affordable homes. Key themes might include assurance of as-built performance, airtightness and ventilation, delivering low-carbon heat, training and skills (both construction and maintenance) and engaging the customer. The route map should include a jointly agreed timetable and targets.
- Initiate and maintain a process for gathering data on as built performance and on the scale and causes of any gap from design predictions. These learnings should be fed back into compliance tools, guidance and assurance processes.
- Review compliance tools so that they best support the delivery of low carbon and ultra-efficient buildings. Priorities linked to operational energy and carbon[24] are:
    - Use of a predefined update cycle that ensures the method incorporates best available data and knowledge. This may require limited processes to enable projects to 'lock-in' to specific compliance tool versions should they wish to avoid disruption
    - Adoption of carbon intensity factors for energy use and exported electricity that better reflect current and projected future values covering at least 10-15 years.
    - Review of efficiency benchmarks for services, lighting and unregulated loads (particularly in non-domestic buildings) to reflect evidence on actual performance and energy use
    - Explicit consideration of levels of peak demand to enable new buildings to minimise their contribution to peak
    - Incorporation of learnings from as built performance reviews to improve the robustness of design predictions and to incentivise the use of relevant product / design / construction standards that have been shown to minimise performance gaps

[24] The CCC have commissioned other studies considering climate adaptation needs and the carbon impacts of construction and building materials that may also need to feed into compliance tools.

- Pathfinder projects, possibly linked to Government funding schemes and the Buildings Mission[25] under the Clean Growth Grand Challenge to help further establish evidence and best practice to support the effective delivery of higher standards for energy efficiency and other future looking requirements such as assessment of whole life carbon performance
- A support body/programme to actively drive change, support the industry, promote innovation, reduce cost and manage risk. This might be similar in form to the former Zero Carbon Hub with representation across government and industry and might be delivered under the auspices of the Clean Growth Grand Challenge and wider Construction Sector Deal.

2 – Transition to low-carbon heat – 2020-2025

Low-carbon heat supply is a priority for delivering long term carbon savings. This study shows that low-carbon heat is cost-effective when built into new homes from 2021 and by 2025 for the limited selection of non-domestic archetypes examined.[26] New homes using low-carbon heat could have lifetime operational carbon emissions that are more than 90% lower than an equivalent gas-heated home. A phased move to low carbon heating is required to manage transition risks and build on the industry support described in Point 1 above, with the aim of all new homes built from 2025 using these technologies. Key steps would include:

- Setting a tighter carbon target that incentivises the use of low carbon heating from 2020. Homes not using low carbon heating technologies would need to achieve significant improvements in efficiency relative to current standards and incorporate design features that reduce the cost of subsequently adopting low carbon heat
- Setting regulations in 2020 which require that all homes built from 2025 utilise low-carbon heating.
- Delivering low-carbon heating in all new homes from 2025 would also require amendments to wider regulations, which currently permit homes to be built to the standards in place at the time planning permission is granted (sometimes many years before the homes are built).

3 - Move to much tighter energy standards for new homes – by the mid-2020s

Tighter energy standards for housing will help to reduce running costs, alongside minimising the contribution of new homes to annual and peak demand. Much tighter standards equivalent to space heating demand of 15kWh/m^2 (when modelled in SAP 2012), together with low-carbon heat, become cost-effective for most house types by 2025 and for all by 2027. Homes built to these standards could reduce annualised household bills by £85-£100.

To manage the transition to tighter energy standards in parallel to a move to low-carbon heat, a phased approach is recommended with tighter standards coming into force in in 2020, 2023 and 2025-7. In advance of standards tightening in 2023 and 2025-7, new developments (including

[25] https://www.gov.uk/government/publications/industrial-strategy-the-grand-challenges/missions#buildings

[26] For the non-domestic archetypes, low-carbon heating is found to be cost-effective in 2025 against the central carbon value only when combined with more efficient lighting. Without improved lighting efficiency the low-carbon heated offices are cost-effective against a high carbon value in 2025. The selected archetypes should be taken as indicative only - further work would be required to assess other non-domestic building types.

but not limited to Pathfinder projects) should be encouraged[27] to go beyond the minimum regulatory requirement and thereby ease the transition to the next level of performance.

Specific performance standards in each year will need to reflect the prevalent compliance method at the time[28] but in addition to incentivising low-carbon heat should focus on ensuring that overall energy use and running costs are minimised and that peaks in demand are avoided / managed effectively.

4 – Tighten energy and carbon standards for new non-domestic buildings 2020-2027

This study shows that there may be opportunity for reductions in the modelled carbon emissions (Building Emission Rate) of 15-25% through energy efficiency based on the non-domestic buildings assessed. Together with low-carbon heat, these measures are cost-effective against a central carbon value in 2025. These changes would deliver lifetime operational carbon savings from 30% to over 80% whilst also reducing running costs. This study only considers two office archetypes and further work would be required to determine standards for a wider range of building types. Nonetheless, there is reason to believe wider opportunities for cost-effective tightening exist in the non-domestic sector.

[27] Consideration could be given to financial incentives for developments going beyond minimum requirements, this approach has been successful in Brussels in supporting their move to Passivhaus standards.
[28] Analysis in this report is based on the SAP 2012 and SBEM 5.6 methods, with amended heating system efficiencies and carbon emission factors, it is expected that any new standards for 2020 will be based on analysis using SAP10 or a successor method and an updated SBEM version.

1. Introduction

The UK has a legally binding target, embedded in the Climate Change Act (CCA), to reduce carbon dioxide equivalent (CO_2e)[29] emissions by at least 80% by 2050, compared to 1990 levels. Recently the Committee on Climate Change was issued with a formal request from the UK and devolved Governments to update its advice on UK climate action following the Paris Agreement, including advice on the date by which the UK should achieve a net-zero greenhouse gas or carbon target.[30]

Around 20% of the homes occupied by 2050 are yet to be built. To comply with legislative commitments, the CCC has found that the energy used to heat and cool our buildings would need to be almost completely decarbonised by 2050[31]. It is therefore imperative that new buildings support this aspiration, particularly in light of the Government's target of building 300,000 homes a year on average by the mid-2020s.[32] The trajectory should be designed to support high quality delivery at scale.

Reducing carbon emissions from buildings can be achieved through a combination of low and zero carbon technologies for heating, cooling and hot water supply and increased energy efficiency. However, the optimum balance between these solutions, from the perspective of managing installation & maintenance costs, carbon performance and consumer bills, has not been assessed in detail for several years. Recent and projected changes in technology costs and, more significantly, in the carbon intensity of electricity mean that it is appropriate to reassess the role of different new build standards in helping meet the UK's climate change targets.

This research project was commissioned by the CCC in February of 2018 to examine the costs and benefits associated with the introduction of more ambitious energy efficiency performance requirements for new buildings, primarily focusing on reducing space heating energy demand, supported by low-carbon heating technologies and accompanied by appropriate design measures to facilitate the improvement.

To illustrate and quantify the value of adopting tighter carbon end energy minimum performance requirements for new buildings, the costs associated with moving to alternate levels of performance are compared against current regulatory requirements and are also compared to the costs incurred if such measures were to be implemented via a retrofit at a future date.

Specifically, this research sought to find answers to the following questions:

- What are the key considerations that should inform the development of future buildings regulatory performance requirements relating to energy and climate change mitigation?
- When does low-carbon heat become cost-effective in new buildings, and what 'future-proofing' steps should be taken to prepare for it?
- What is the role of improved efficiency, and how could this be improved in new buildings alongside low-carbon heat uptake?
- What are the associated costs and how might these differ if the same, or similar, standards were achieved subsequently via retrofit?

[29] For the purposes of this research report, the term 'carbon' is used to refer to carbon dioxide equivalent (CO_2e) emissions, the primary metric of greenhouse gas emissions.
[30] A copy of the letter requesting advice is available here.
[31] Committee on Climate Change, 2016. Next steps for UK heat policy.
[32] HM Treasury, 2017. Autumn Budget 2017, Building the homes the country needs.

- How should current regulatory requirements and associated compliance tools (e.g. SAP and SBEM) be developed in the short and medium term to help deliver buildings that are high quality, affordable, very low carbon and support efforts to decarbonise the wider energy system[33]?

This scope of this study has been focused on the energy, carbon and cost impacts of reducing space heating demand, alongside low-carbon heat uptake. It does not explore the potential for carbon savings arising from other measures to drive hot water efficiency improvements (for example, water efficient showers, baths and taps, solar water heating or waste water heat recovery) or reductions in unregulated energy consumption. There are likely to be further opportunities for improvements in these areas, which are now being recognised in modern predictive performance assessment methods and compliance tools[34].

Operational carbon emissions are only one component of the whole life carbon impact of a building. The construction process and the manufacturing and supply of construction materials both give rise to additional carbon emissions. Furthermore, the use of wood in construction can sequester carbon from the air, providing a route to deliver carbon reductions. In 2018 the CCC published a study[35] into the role of biomass in a low carbon economy. This study reiterated the importance of wood in construction as one of the best uses of biomass to achieve carbon reductions. An associated study[36] considers these issues further and examines the opportunities for incorporating embodied and sequestered carbon into the building standards framework to drive whole life carbon reductions.

[33] For example, by reducing overall and peak levels of energy demand.
[34] For example, the new SAP 10 assessment method now requires consideration of the impact of specific shower flow rates on levels of hot water demand and associated energy and carbon emissions.
[35] Committee on Climate Change, 2018. Biomass in a low carbon economy.
[36] AECOM for the Committee on Climate Change, 2019. Options for incorporating embodied and sequestered carbon into the building standards framework.

2. Policy context

Following the revocation of the Zero Carbon Homes policy, which was to be introduced in 2016, it is several years since there was a substantial update to minimum regulatory requirements for the energy and carbon performance of new buildings in the UK. No revision was made to Approved Document L (Part L) in England in 2016, so requirements for energy and carbon have been unchanged since the 2013 review that came into force in 2014. In Wales, Part L was last reviewed and updated in 2014, while in Northern Ireland, Part F was most recently updated in 2012 and in Scotland Building Standards Section 6 was revised in 2015. The next reviews of Part L for England and for Wales are expected to go to consultation in 2019, while the Scottish Government published a call for evidence in relation to the future of its building standards in the summer of 2018.

Energy and carbon performance requirements vary across the UK in the level at which the target emission rate (TER) for new buildings is defined. However, each of the requirements used across the UK refer to the same compliance tools which include the Standard Assessment Procedure (currently SAP 2012) for domestic buildings, and SBEM or dynamic models for non-domestic buildings.

While minimum performance requirements have not changed substantially in recent years, 2018 saw several important reviews and initiatives which help to inform their future direction. These include the Hackitt Review, Building a Safer Future[37], and the Government's Industrial[38] and Clean Growth[39] Strategies.

2.1 Hackitt Review

Although not focused on the energy and carbon performance of buildings, the Hackitt review identified a range of systemic issues relating to compliance and enforcement which mean some buildings are not meeting required standards. The review includes a recommendation for a move to a more 'outcomes based' approach to building safety. It also recognises that buildings' systems are not isolated components, so a more holistic approach needs to be considered. Finally, it recognises the necessity for clearer ownership of risk between construction stakeholders, and the lack of a transparent audit trail running throughout the building's life.

Whilst not analogous, these themes resonate strongly with previous research on the energy 'performance gap'[40] where a complex series of factors are believed to result in buildings failing to achieve the levels of energy performance predicted during their as-built compliance assessments.

2.2 Industrial Strategy

The Department of Business, Energy and Industrial Strategy (BEIS) set out in their 2018 Industrial Strategy a series of 'Grand Challenges'. The purpose of these is *"to put the UK at the forefront of the industries of the future, ensuring that the UK takes advantage of major global changes, improving people's lives and the country's productivity"*.

[37] MHCLG,2018. Building a safer future: Independent Review of Building Regulations and Fire Safety: Final Report.
[38] BEIS, 2018. Industrial Strategy: building a Britain fit for the future
[39] BEIS, 2018. The Grand Challenges
[40] Zero Caron Hub, 2014. Closing the gap between design & as-built performance: End of term report
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The first four Grand Challenges are:

- Artificial Intelligence and data
- Ageing society
- **Clean growth**
- Future of mobility

The first Mission under the Clean Growth challenge is the Buildings Mission, with the objective to: *At least halve the energy use of new buildings by 2030*. This is planned to be achieved by:

- Making every new building safe, high quality, much more energy efficient and use clean heating
- Making low energy, low carbon buildings cheaper to build
- Driving lower carbon, lower cost and higher quality construction through innovative techniques
- Giving consumers more control over how they use energy through smart technologies
- Halving the cost of renovating existing buildings to a similar standard as new buildings, while increasing quality and safety

The mission is backed by £170 million of public money investment budget offered through the Transforming Construction Industrial Strategy Challenge Fund. BEIS expect this will be matched by £250 million of private sector investment, totalling over £400 million of investment on Clean Growth solutions. The Mission will also be supported through the 'Home of 2030' design competition. The Buildings Mission is expected to launch a Call for Evidence in 2019 to share initial thinking and seek views.

2.3 Construction Sector Deal

In addition to the specific funding for the Grand Challenge Clean Growth Mission, the Government has made additional support available to the construction sector through 'The Construction Sector Deal'. The deal sets out a partnership between the government and industry and aims to increase the sector's productivity. Productivity gains are expected to be achieved by using innovative technologies and through the training and development of a highly skilled workforce.

More than £600 billion of spending is expected to be allocated to the sector over the next decade, including at least £44 billion in funds allocated for housing.

Envisaged benefits include:

- Better, cheaper-to-run homes
- Smarter and safer buildings
- Lower overall carbon emissions from buildings, leading cleaner air

The Construction Sector Deal aims to support the Clean Growth Grand Challenge.

2.4 Summary

Against a backdrop of relatively little regulatory change in minimum buildings' energy and carbon performance requirements over recent years, there are now several initiatives that imply growing ambition in achieving improved performance.

Importantly, improved in-use energy and carbon performance is defined as a component of initiatives to improve building quality and affordability where innovative technologies and thinking enable these objectives to be delivered concurrently.

In this context, it is timely to consider the potential for building to higher energy and carbon standards as part of wider moves towards improved productivity and quality within the sector.

3. Review of 'best practice' energy and carbon standards

A review of selected operational energy and / or carbon standards for new buildings was undertaken to inform the performance standards analysed within this project.

National and international carbon and energy performance standards for new homes, along with examples of the implementation of the European Energy Performance of Buildings Directive (EPBD[41]) in two EU Member States, were selected for a cross-comparison review.

The focus was on 'best practice' standards[42] that are reasonably ambitious compared to the current requirements of the 2013 Building Regulations in England.

The comparative assessment focuses on their scope, level of ambition and the metrics used for target setting. Other elements considered included key methodological differences/ assumptions that affect energy demand analysis, technological approaches (where mandated), and quality assurance procedures.

The standards reviewed are shown below:

- England and Wales Part L 2013 (reference case)
- Greater London Authority (GLA) draft London Plan targets
- Energiesprong
- Passivhaus
- Passivhaus Plus
- Zero Carbon Hub (ZCH) Advanced Energy Efficiency specification with ASHPs[43]
- Zero carbon (previously Code for Sustainable Homes level 6) target[44]
- Netherlands Nearly Zero Energy Buildings (NZEB) standard
- Denmark NZEB standard

Key aspects of the standards reviewed are summarised in Appendix A.

3.1 Scope

All of the mandatory national or local requirements reviewed (Part L, GLA London Plan, Dutch and Danish NZEB definition and the Zero Carbon Homes definition) exclude unregulated energy use (typically comprising small power, appliances and cooking).

Unregulated energy use is considered in the case of Passivhaus, Energiesprong and (the now redundant) Code for Sustainable Homes Level 6. However, none of the performance standards reviewed included considerations around embodied or sequestered carbon in their targets.

Part L 2013, the GLA London Plan, Passivhaus, and the Danish NZEB standard include compliance requirements for thermal comfort and/or overheating, though the complexity and

[41] The European Energy Performance of Buildings Directive (EPBD) requires all new buildings to be nearly zero-energy by the end of 2020. All new public buildings must be nearly zero-energy by 2018. The Netherlands and Denmark were included in this study as being representative of ambitious but differing approaches to delivering NZEB objectives.
[42] Standards in this context could range from a regulatory requirement to planning policy or a certification / accreditation.
[43] Zero Carbon Hub, Cost Analysis: Meeting the Zero Carbon Standard, February 2014. The standard assessed is referred to as Scenario 7 in the report.
[44] For more details on the standard, refer to the technical guide available on https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/5976/code_for_sustainable_homes_techguide.pdf

rigour of the assessment varies. The use of dynamic thermal simulation and future weather data for assessing GLA London Plan compliance makes the assessment more robust, while Part L 2013 compliance is based on a simple overheating check as driven through Appendix P of the Standard Assessment Procedure (SAP).[45]

3.2 Ambition

A like-for-like comparison between standards is challenging given the range of metrics used, differences in scope (i.e. energy end uses included in the standard) and differences in underlying assumptions (e.g. occupancy and weather data). These variations mean that achieving the same performance standards can require different design or specification solutions both between differing compliance methods and even within the same method where key reference values are changed such as the carbon intensity of different fuels.

Indicative figures to compare the different standards, when applied to domestic buildings, are shown in Appendix A. The upper and lower end of the ranges are derived based on a 1-bed flat (small dwelling; efficient form) and a 4-bed detached house (large dwelling with much higher heat loss area). The comparison is based on a dwelling level air source heat pump (ASHP) delivering space heating and hot water.

Note that the differences in calculation method/tools, assumptions and quality assurance procedures may make it relatively easier or more difficult to achieve a target value (e.g. the specification required to deliver a target space heating demand of 15kWh/m^2/yr will differ under Part L compared to Passivhaus). Also, the 'indicative' primary energy values for Part L, ZCH Scenario, GLA London Plan and Code Level 6 dwellings are based on SAP 2012 conversion factors and these may again differ from the primary energy conversion values used under the other standards.

The review suggests that the delivered energy requirements for the Energiesprong standard, Passivhaus Plus and Code level 6 are somewhat similar when comparing on the basis of an electric heating system at the dwelling level[46] (acknowledging the differences in metrics used, underlying assumptions and methodologies). I.e. they all aim to achieve net zero delivered regulated and unregulated energy over the course of a year. The Code 6 target is set in terms of net zero annual CO_2 emissions from regulated and unregulated energy uses. A comparison based on all electric heating at dwelling level would translate to net zero energy over the year.

However, there are areas where the Passivhaus Plus standard sets a higher performance standard than other exemplar standards:

- the space heating demand standard in Passivhaus is half that of Energiesprong. This will help to reduce overall and peak energy demand for heating, limiting the amount of energy generation and network infrastructure required at the system level. However, the scale of any additional peak reduction benefit from a Passivhaus space heating standard in comparison to that required by Energiesprong is difficult to quantify without more detailed dynamic simulation.
- the Passivhaus Plus standard incorporates a unique metric known as Primary Energy Renewable (PER). This considers the timing of energy generation and demand and

[45] The Building Regulations Part L Approved Documents include limiting effects of heat gains in summer, however the main purpose is for conservation of fuel and power (to limit solar gain to either eliminate or reduce the need for air conditioning).
[46] The target is set in terms of net zero annual CO_2 emissions from regulated and unregulated energy uses. A comparison based on all electric heating at dwelling level would translate to net zero primary energy over the year.

makes an allowance for possible energy losses associated with medium term (inter-seasonal) energy storage. In so doing, the PER standard provides a refinement on any 'net' zero assessment by explicitly acknowledging that there is an efficiency cost where generation and demand are not synchronised.

3.3 Targets and metrics

The standards reviewed use a range of metrics to set targets including space heating and/or cooling demand (the Part L Target Fabric Energy Efficiency being a variant of that, calculated under specific conditions), carbon emissions, delivered energy, primary energy, or performance ratios set relative to another standard/ baseline.

Mandatory regulatory requirements are developed to evaluate performance as estimated by the different approved assessment calculation methods. Such elements mainly address a 'design intent' and usually do not refer to operational performance or take into account variations in energy supply during the lifecycle of the property. This is an important consideration where (as is the case in the UK) the energy system is undergoing significant change both in terms of generation mix and in the demand for electricity.

Often, more than one metric is used within the overall approach, e.g. a space heating/ energy demand requirement indicating the performance at a building level, along with a carbon or primary energy metric that captures the implications of the building's performance on the wider environment. Once minimum building elements performance requirements are met, nearly all approaches allow for additional performance-based targets to be achieved through a combination of increased energy efficiency systems, and energy generation solutions without mandating the use of specific system technologies. The exception to this is the Danish regulations that require solar thermal system installations for dwellings with hot water consumption above a certain threshold.

Energiesprong, Passivhaus and the Danish NZEB set energy and carbon performance targets irrespective of building form and size, though these could differ between different building uses (i.e. for domestic and commercial buildings).

The Zero Carbon Hub Advanced Practice specification (in the way it would have been applied) is more akin to an elemental approach having prescriptive requirements in terms of homes' fabric and carbon performance, while the remaining approaches set improvement targets relative to a notional building.

One of the key limitations of the way the notional building is defined currently under Part L, is that it does not reward an efficient built form. Absolute performance requirements, as seen in other approaches, may make it harder/ less cost-effective for some typologies to meet the targets (e.g. dwellings with large heat loss areas).

For nearly all the approaches reviewed, compliance is assessed using modelled performance. The exception to this is Energiesprong, which puts in place performance guarantees based on measured / monitored operational energy consumption.

3.4 Summary and opportunities for adopting best practice

The review highlights the diverse range of approaches adopted by different national regulatory requirements and exemplar standards. The choice of performance metrics and the level of ambition will influence design decisions and trade-offs at the building level. Building level requirements should be set to a level that considers both building scale and system level costs and impact.

Within this review several features were identified which could support a transition towards a more holistic assessment of targets set for the energy and carbon performance of buildings. These include:

Focussing on actual rather than modelled performance
Most of the reviewed performance evaluation approaches focus on predicted energy consumption and carbon emissions. The Energiesprong standard however is based on guaranteed actual measured energy consumption. The use of actual energy performance targets, even if only for part of the overall energy use, would help to focus the attention of designers and builders on delivering robust, buildable, high quality units, where predicted performance better aligns with energy consumption in-use[47]. Targets of this kind have potential to drive a cultural shift across the supply chain and in compliance and enforcement.

Some planning authorities (e.g. the Greater London Authority) are also looking to require the operational energy use of new development to be reported after completion[48].

Although not linked to specific energy performance thresholds, as is the case for Energiesprong, the act of reporting energy consumption of individual buildings built to specific standards would help increase the evidence base in relation to the performance gap and prompt increased awareness of the distinction between design projections and actual energy use.

Work undertaken on reducing the performance gap in new housing by the Zero Carbon Hub[49] describes some of the regulatory and other measures that could be adopted to help improve in-use performance.

Higher levels of ambition
Standards in both the Netherlands and Denmark are higher than those currently in place in the UK, both for overall performance and in relation to space heating demand. The ability of some countries to set higher regulatory requirements demonstrates that these levels of performance can be achieved routinely in new development.

Explicit requirements on thermal comfort and overheating
Some of the reviewed standards demonstrate more advanced methods for assessing internal thermal comfort and overheating risks. This is a result of additional functional requirements added to the assessment process relating to ventilation performance, building design, internal gains, heat distribution evaluation and patterns of use.

Enabling a comfortable internal environment to be maintained is important in achieving predicted energy consumption, reducing the risk of inefficient / unnecessary cooling systems being installed, and most importantly in maintaining the health and well-being of the householder.

Recognising and rewarding efficient build form
UK regulatory requirements for energy and carbon are based on assessments in comparison to a notional dimensionally identical building. The notional building has a set elemental performance specification and the modelled performance of the new building must be equivalent or better than that of the notional building. Under this approach, buildings that are inherently less efficient, i.e.

[47] If usage pattern assumptions are followed
[48] GLA, 2018. Draft new London Plan. The scope of buildings affected by the policy and the information to be reported is still to be confirmed.
[49] Zero Carbon Hub, 2014. Closing the gap between design and as built performance: End of term report.

with a higher external surface to internal area ratio, are permitted to use more energy and emit more carbon than those where the building form is more efficient.

Whilst the notional building approach enables a relatively consistent construction specification approach to be applied to different buildings, it also means that some new buildings will be significantly less energy and carbon efficient than others. For example, in this study, the energy consumption for space heating of the notional buildings for each housing archetype varied from under 30 kWh per m^2 to over 45kWh per m^2. Homes with higher heating requirements per m^2 may make a greater contribution to peak energy demand and may have more limited capability to pre-heat their homes as a route to manage their use at peak times. Both these factors are increasingly important where the heating system is electricity-based. Higher peak demand will increase overall energy system costs and could increase individual householders' bills in the context of time of use tariffs.

Absolute performance targets for energy consumption are in place in Denmark and also within exemplar standards such as Passivhaus and Energiesprong.

Assessment of peak heating / cooling loads

The method[50] used in the Passivhaus standard includes assessment of the peak heating or cooling loads likely to arise in two different worst-case scenarios. Targeting specific peak heating / cooling loads would help in managing levels of peak demand which would be particularly beneficial in the case of electrically heated buildings. Subject to a robust demonstration of the relationship between specific peak loads and levels of thermal inertia, this analysis could also form a reasonable indication of the level of inherent heating flexibility that could enable heating to be operated during specified (e.g. off-peak) periods.

Importance of heating decarbonisation over 'net emissions'

Current UK regulatory requirements enable onsite energy generation (e.g. via photovoltaics) to reduce the net emissions of a building so, in theory, a building could achieve zero carbon status whilst still using a gas heating system. As the electricity grid continues to decarbonise the drawbacks of this approach become more apparent as the relative benefits of the renewable energy generated on site become smaller while the emissions from gas consumption are unchanged. Onsite electricity generation is not a substitute for reducing and decarbonising heat.

As further concern with a direct 1:1 net approach between onsite and grid supplied electricity is the timing and intensity of use. For example, under an electric heating scenario, electricity demand may be particularly high during a cold winter night, the surplus energy supplied by a PV system during warmer summer days is of little benefit in meeting this demand unless the power can be stored effectively. This storage has costs in both financial and energy (conversion losses) terms.

The PER metric used in Passivhaus Plus provides one method for capturing the impact of synchronicity of energy generation and demand enabling more representative consideration of the value of onsite generation.

[50] The Passivhaus Planning Package (PHPP) method and spreadsheet model.

4. Research method

Energy efficient performance standards were defined for selected domestic and non-domestic building archetypes. These were then combined with either traditional gas heating systems, Air Source Heat Pumps (ASHP) or low-carbon heat networks (LCHN) for the supply of heating and hot water. The report is not intended to be a comprehensive look across all low-carbon heating technologies – rather, the method focuses on a limited number of technologies to inform views of cost-effective potential for tightening building regulations.

The lifetime costs (incorporating capital costs, fuel costs,[51] and replacement and maintenance costs) and carbon savings (both direct and indirect) associated with packages were modelled, with the incremental costs and savings set against a counterfactual of a home built to the English Part L 2013[52] notional specification with gas heating. The social cost-effectiveness of these packages was then assessed. The cost-effectiveness of a package of measures to reduce emissions can be evaluated by its abatement cost. Expressed in £/tCO_2e, the abatement cost is the total lifetime cost of the package of measures divided by the associated total lifetime emissions savings.[53,54] A measure is considered cost-effective if its abatement cost is lower than the appropriate, target-consistent carbon value. Both central and high carbon values were used to assess the cost-effectiveness of tighter standards. High carbon values are of particular interest in the context of the recent request made by UK and devolved Governments for advice on the date by which the UK should achieve a net zero greenhouse gas or carbon target.[55]

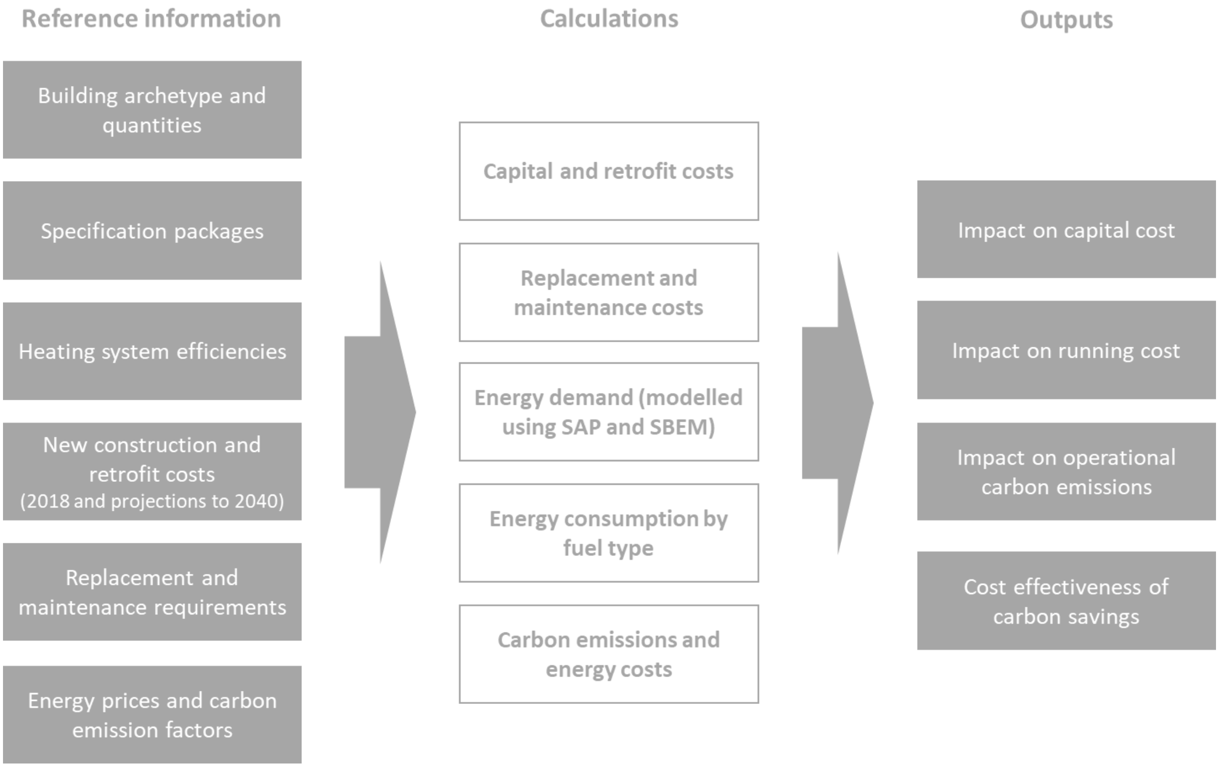
In addition to evaluating the social cost-effectiveness of packages of low-carbon heating and energy efficiency measures, the analysis also examined the bill impacts associated with measures and the costs of implementing these packages in new build homes, relative to the costs of retrofitting at a later date. The aim of this latter exercise was to determine the relative difference in costs between acting now to set higher standards or seeking to achieve the same outcomes retrospectively.

The analysis was conducted using existing SAP 2012 and SBEM 5.5 compliance tools to predict the building models' energy performance, with bespoke assumptions used for the efficiencies of different heating and hot water systems, predicted energy costs, and for the carbon intensity of delivered energy. These amendments were necessary to reflect the latest evidence on current technology performance and the CCC's projections for energy prices and carbon factors.

Figure 4.1 summarises the key elements of the modelling approach used for each combination of building archetype and specification.

[51] Long run variable costs were used for the purposes of determining lifetime costs. Retail costs were modelled separately in order to generate estimates of bill savings.
[52] The English standard was selected as the comparator as it has the most substantial impact on the overall performance of new housing in the UK and is currently one of the least ambitious UK standards.
[53] Carbon values for policy appraisal are designed to be consistent with action required under the Climate Change Act. The abatement cost of a package of measures is compared against the average discounted carbon value across the lifetime of the measures. For further information on the CCC's approach to assessing cost-effectiveness, see Committee on Climate Change (2015) *Sectoral Scenarios for the Fifth Carbon Budget – Technical report*, box 1.2.
[54] Based on the net present value of the differences in capital, maintenance and variable energy costs set against annual carbon savings over 60 years.
[55] See:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/748489/CCC_commission_for_Paris_Advice_-_Scot__UK.pdf

Figure 4.1 Summary of modelling approach



Key elements of the research method are described below. Further detail is included in Appendices.

4.1 Building archetypes

The study prioritised analysis of domestic buildings as these represent the largest component of future construction. Four home types were considered:

- detached (117m^2)
- semi-detached (84m^2)
- low rise flat (2 bed, 70m^2)
- high rise flat (1 bed, 50m^2)

The home designs were consistent with those used previously by government for the assessment of Part L amendments in 2013. The selected house types provide for a range of sizes, form factors and approaches to the supply of heating and hot water to be evaluated in the study.

The 'core' home type used in the analysis is the semi-detached house. This type represents c.29% of new homes built each year and is used by CCC as being representative of the 'typical household'.

Two non-domestic buildings were considered, a naturally ventilated office and an air-conditioned office. The wide diversity of non-domestic building types and their respective energy demands mean that these selected archetypes are only illustrative of some of the relevant issues and conclusions should not be taken as representative of the wider non-domestic sector.

Further information on each archetype is provided in Appendix B.

4.2 Specification packages

Specification packages were developed to achieve enhanced efficiency beyond the requirements of English Part L 2013. The approach for domestic and non-domestic buildings differed, with domestic buildings targeting reduced absolute levels of space heating demand, and non-domestic buildings targeting percentage improvements over the performance of a notional building. The approach for non-domestic buildings was different on the basis that space heating demand is considered a less significant overall contributor to carbon emissions.

The energy and carbon model thresholds used for each building type are shown in Table 4.1.

Table 4.1 Targeted energy and carbon performance levels

Standard		Archetype			
Domestic archetypes		Detached house	Semi-detached house	Low rise (large) flat	High rise (small) flat
Space heating demand at Part L 2013 Notional Specification (kWh m^2 per year)		43.7	36.9	33.2	26.0
Space heating demand (kWh m^2 per year)	35	Yes	No	No	No
	30	Yes	Yes	No	No
	25	Yes	Yes	Yes	No
	20	Yes	Yes	Yes	Yes
	15	Yes	Yes	Yes	Yes
Non-domestic archetypes		Naturally ventilated office		Air-conditioned office	
Percentage reduction in carbon emissions beyond the requirement of Part L 2013	15%	Yes		Yes	
	20%	Yes		Yes	
	25%	Yes		Yes	

Achieving improved performance

The technical solutions considered in the models to achieve energy and CO_2e thresholds included:

- higher fabric energy efficiency using improved U-values for walls, roof, floors, and windows and thermal bridging y-values
- reduced air leakage
- use of mechanical extract and heat recovery ventilation
- solar control glazing (non-domestic buildings)
- energy efficient lighting and improved controls (non-domestic buildings)
- highly efficient air handling and terminal units (non-domestic buildings)
- use of more efficient heating and cooling systems (non-domestic buildings)

While a range of building forms were considered in the study, the option to change the form factor of the building archetype or to change glazing ratios or other core design features were not explored.

Domestic performance specifications

Modelled elemental performance variations compared to minimum requirements of the Part L 2013 notional building[56] are shown in Table 4.2. The specific packages of measures together with their modelled energy performance are shown in Appendix C.

Table 4.2 Energy efficiency options considered for domestic buildings

Category		Part L Notional	Other options modelled
Walls	Exposed (W/m².K)	0.18	0.17, 0.15, 0.13
	Semi exposed (W/m².K)	N/A, 0.21	
Floors	Ground Floor (W/m².K)	0.13	0.15, 0.11
Roofs	Exposed Roof (W/m².K)	0.13	0.11
Doors	U-value (W/m².K)	1.0	1.2
Windows	U-value (W/m².K)	1.4	1.2, 0.8
Ventilation	Type	Natural ventilation with local extract in kitchen and wet rooms.	Whole house mechanical ventilation and heat recovery
Air Permeability	(m³/h.m² @50pa)	5.0	3.0, 2.0, 1.0
Thermal Bridging	Y-value	0.05	0.04
Heating distribution system		Radiators suitable for 'higher' (a flow temperature of c.60ºC) temperature heating	Radiators suitable for 'low' (a flow temperature of c.40ºC) temperature heating
Basic overheating prevention		None	Use of inward opening windows and external shutters
Energy storage		None	Lithium Ion battery storage (2kWh capacity) Use of thermal store to reduce peak energy for heating

[56] Some developers will typically build to less energy efficient standards than the Part L 2013 notional specification, particularly where there is a need to install renewable energy to meet planning requirements. The notional specification was selected as it comprises a compliant method that does not use onsite photovoltaics and is therefore consistent with the other options under consideration.

Airtight, mechanically ventilated homes

To achieve the most significant reductions in space heating demand, increased airtightness levels were used in combination with mechanical ventilation heat recovery (MVHR) systems.

Higher levels of airtightness were achieved using wet plaster finish on external walls, taping around openings and ceiling junction and use of a membrane / boarding over ceiling joists. Achieving high levels of air tightness routinely on a large volume of homes is a challenge as the tolerances are tight and it is recognised that investment would be needed at an industry wide level to support upskilling of design and project teams to enable these levels of quality to be achieved routinely.

Sensitivity analysis was undertaken to test the impact of varying airtightness levels on the external wall U-value needed to meet specific space heating standards. This analysis showed that, for a semi-detached house, improving airtightness from 2.0 m^3m^2hr to 1.0 m^3m^2hr enabled wall U-values to be increased from 0.16 Wm^2/K to 0.22 Wm^2/K while still meeting a space heating demand of 15 $kWh/m^2/yr$. This analysis suggests that where homes are very airtight and have a reasonable form factor (i.e. a compact dwelling, ideally with adjoining units) it is possible to achieve very low levels of space heating demand whilst retaining external wall specifications that are at, or are even slightly above, those of the Part L 2013 notional building specification. However, for the modelled detached house, it was necessary to combine high airtightness (1.0 m^3m^2hr) and low U values (0.13 Wm^2/K) to achieve the 15 $kWh/m^2/yr$ standard. This reflects the much higher ratio of external envelope to internal floor area in these homes in comparison to the other modelled archetypes.

To achieve very low levels of space heating demand in houses it was necessary to use MVHR systems[57]. While providing significant potential energy efficiency benefits, MVHR systems need to be appropriately integrated within a home design and then installed, commissioned and maintained appropriately. Studies reviewed by the Zero Carbon Hub[58] identified a wide range of issues covering all stages from design to maintenance. The study identified good practice measures to help ensure the MVHR unit performs as intended. While the industry has increasing experience in using MVHR, particularly within flats, further support would be needed to facilitate effective wider adoption of the technology.

To provide a more realistic comparison between new build and retrofit costs, the retrofit specifications were very slightly modified to avoid the need to undertake significant retrofit work for a very small improvement in building performance where relevant (for example, retrofit of a ground floor to move from a U value of 0.13 to 0.11 Wm^2K). Where the retrofit models were amended to incorporate a more pragmatic retrofit option, the impact of the specification change on the lifecycle operational performance analysis was also considered.

Non-domestic buildings

Options for improving the efficiency of the naturally ventilated and air-conditioned office are shown in table 4.3.

[57] The use of whole house mechanical extract ventilation was considered. However, due to the lack of the heat recovery, these solutions were unable to meet the lowest space heating demand targets using SAP 2012 modelling assumptions. The tightest standards (25$kWh/m^2/yr$ and below) cannot be achieved without improved airtightness and the use of MVHR systems in at least some archetypes. 15$kWh/m^2/yr$ would require MVHR in all.

[58] Zero Carbon Hub, 2013. Mechanical Ventilation with Heat Recovery in New Homes. Final Report.

Table 4.3 Energy efficiency options considered for non-domestic buildings

Category		Part L Notional	Other options modelled
Walls	Exposed (W/m².K)	0.26	0.18, 0.15
Floors	Ground Floor (W/m².K)	0.22	0.15
Roofs	Exposed Roof (W/m².K)	0.18	0.15, 0.12
Windows	U-value (W/m².K) G-value	1.6 0.40	1.4, 1.2 0.40
Air Permeability	(m³/h.m² @50pa)	3.0	
Ventilation	Type	Natural ventilation High efficiency air handling unit and ducts with SFP of 1.8 watts per second and heat recovery of 70% Fan coil units with fan power of 0.3 watts per second	Natural ventilation Heat recovery of 80% Fan coil units with fan power of 0.18 watts per second
Cooling*		None with natural ventilation Air conditioning with air cooled chiller (SSEER 3.6)	- Air conditioning with high efficiency chiller (SSEER 4.3)
Lighting	Office floor lighting (Luminaire lumens per circuit watt)	60	75, 95
Note: * where an ASHP is specified for the air-conditioned office this is designed to be capable of providing both heating and cooling.			

4.3 Heating systems, heating distribution and emitters

For both domestic and non-domestic buildings, heating systems options comprised gas boilers, air source heat pumps and low-carbon heat networks.

The efficiency of each system was specified to reflect existing CCC modelling assumptions[59] and data gathered from the installation of systems in use[60]. In the case of ASHPs, future improvements in system efficiency were also incorporated within the models to recognise the ongoing refinement of the technology and its use within new buildings.

Domestic buildings

The specifications for each of the heating systems when applied to domestic buildings are shown in table 4.4.

Table 4.4 Domestic heating system specifications

System	Modelled efficiency	Specification for each house type
Gas boiler	89% (efficiency was increased by 3% where the boiler was paired with low temperature radiators)	▪ Detached - System boiler and cylinder ▪ Semi-detached - Combi boiler ▪ Large (low-rise) flat – Combi boiler ▪ Small (high rise) flat – centralised boiler and storage with heat interface unit for each flat. Heat losses of c.9% within block level distribution.

[59] Committee on Climate Change, 2015. Sectoral scenarios for the Fifth Carbon Budget.
[60] UCL Energy Institute, 2017. Final report on analysis of heat pump data from the Renewable Heat Premium Payment (RHPP) scheme.

Air source heat pump	300% for space heating - improving by 5% per year for homes installed between 2018 and 2028 (i.e. efficiency is 350% for installations in 2028) 230% for domestic hot water	▪ Detached, semi and large flats – split external and internal units with hot water cylinder ▪ Small flats - centralised system and storage with heat interface unit for each flat. 70% of heating supplied by ASHP with balance (including winter peaks) met by gas boilers[61].
Low-carbon heat network	70% supply via high efficiency water source heat pump (400% efficient) and 30% by 92% efficient gas boiler. Heat losses of c.5% within heat network.	▪ Heat interface unit provides instantaneous heating and hot water with heat storage undertaken within the network ▪ Costs of heat supplied assume that the network is operating in a high heat density area[62]

The ratio of heat demand for space heating and hot water for each building type and efficiency level is included in Appendix C.

Heating distribution solutions were considered in each model (in each case as appropriate to the heating technology). These included underfloor heating and also radiators sized to allow for low temperature heat delivery. Analysis in SAP did not highlight a significant energy reduction benefit from using underfloor heating when compared to appropriately sized radiators running at the same temperature and so modelling was conducted using radiators as these are less expensive to install. Nevertheless, underfloor heating systems do potentially offer additional benefits in some circumstances, not least by avoiding the need for radiators on walls which increases the flexibility of internal layouts. In very energy efficient buildings, the need for additional heating is low and so the expense of underfloor heating in comparison to relatively few radiators would be even more significant.

In terms of in-house heat distribution networks and emitters, the size of the system was adjusted for each model to address the heating demand requirement. For example, models that required very little heat to achieve a comfortable indoor environment would have shorter heating distribution pipework and a reduced number of radiators. This approach was developed from feedback received from those delivering very energy efficient homes, e.g. to certified Passivhaus or close to Passivhaus standards. In terms of associated cost saving, a 75% reduction of the combined cost of radiators and associated heating distribution pipework was incorporated in the housing models with a space heating demand lower than 15kWh/m^2/year. For this level of performance, the emitters were considered to have moved towards the core of the house.

Smaller proportionate savings were assigned to the other models with higher heating demand performance levels.

Table 4.5 summarises the percentage reductions in heating system distribution costs used for homes with very low space heating demand.

Table 4.5 Reductions in heat emitter and internal distribution system costs in homes with low space heating demand

Space heating demand	Houses	Flats
Above 25kWh m^2	0%	0%
25kWh m^2	25%	0%

61 An alternative approach with 100% of heating demand met by ASHPs was also tested as a sensitivity (see section 5.9 and appendices).
62 Equivalent to that for 'Group 8' heat density defined in Element Energy, 2015. Research on district heating and local approaches to heat decarbonisation.

20kWh m^2	50%	25%
15kWh m^2	75%	50%

It should be stressed that examples of reduced heating systems in housing are typically linked to the use of certified Passivhaus. Passivhaus certification requires a robust, and audited, quality assurance (QA) process to be followed in terms of skills, construction methods used and delivered product quality. As a result, the risk that the completed home will have substantially higher heat loss than predicted is minimised.

If as built performance is not as good as that intended at the design stage, the additional losses might mean that the reduced heating system would be insufficient to maintain comfortable temperatures, thereby limiting the applicability of this approach. Research to date suggests that, where investigated, a substantial gap is identified between the design and as built performance of new UK homes. Therefore, to be confident in applying such cost savings initiatives in new homes, it would be of critical importance that the performance gap is addressed alongside any uplift to standards.

The implications of different assumptions for reducing heating system costs on the cost-effectiveness of different design standards are examined as part of sensitivity analyses (see Section 5.8.

Non-domestic buildings

The specifications for each of the heating systems when applied to domestic buildings are shown in table 4.5.

Table 4.5 Non-domestic heating system specifications

System	Modelled efficiency	Specification for each house type
Gas boiler	ScoP of 82% to 88% depending on scenario and building type	▪ Boiler providing space heating and domestic hot water
Air source heat pump	320% for space heating - improving by 5% per year for homes installed between 2018 and 2028 (i.e. efficiency is 370% for installations in 2028) 220% for hot water	▪ Naturally ventilated office – heat pump provides 100% of space heating and hot water demand ▪ Air-conditioned office – heat pump provides both heating and cooling and is sized to meet peak cooling demand which is greater than that for heat.
Low-carbon heat network	70% supply via high efficiency water source heat pump (400% efficient) and 30% by 92% efficient gas boiler. Heat losses of c.5% within heat network.	▪ Plate heat exchanger provides access to heat for space heating and hot water ▪ Costs of heat supplied assume that the network is operating in a high heat density area[63]

4.4 New construction and retrofit costs

The developed costs were based on the expert view of Currie & Brown's cost specialists, drawing on evidence from internal cost datasets, existing published cost data and information provided by product suppliers and both large and small housebuilders.

[63] Equivalent to that for 'Group 8' heat density defined in Element Energy, 2015. Research on district heating and local approaches to heat decarbonisation.

The cost analysis is intended to reflect typical national costs from Q4 2017 that might be incurred by a medium sized housebuilder using traditional (i.e. masonry) construction methods and with a reasonably efficient supply chain, design development and construction processes. However, costs incurred by individual organisations will vary according to their procurement strategies, the location of their activity (e.g. costs will be higher in London and the South East of England) and the detail of their housing product. These variations in cost were captured as adjustments to the base cost data and used to undertake sensitivity analysis to assess the implications for projects subject to higher or lower costs.

For low-carbon heat networks, the costs of establishing and operating the network providing heat to the building were captured using previous work for CCC by Element Energy[64] on the levelised cost of energy (LCOE) for heat networks using different heating sources and with varying levels of heat demand density. While the LCOE provides a reasonable assessment of the social costs of establishing and running a network it does not necessarily reflect the capital costs to which a developer may be exposed as these will vary according to whether the project is establishing a new network or connecting to existing infrastructure. Given this study only sought to include LCHN on an illustrative basis due to the substantial variation in costs that may arise, the results only address the relative costs of connecting to LCHN with different levels of energy efficiency and do not estimate implications for running costs or overall cost-effectiveness.

To provide context to the cost variations assessed in the study an indicative overall build cost (£ per m^2) for each building archetype was estimated using Currie & Brown internal data. This figure is indicative of the level of cost that might be expected for a home built in accordance with the requirements of Part 2013. The build cost should be taken as indicative only as it is sensitive to a wide range of design and specification variables in addition to the economies of scale and regional variations discussed below.

Appendix D includes details of the cost information used for each specification option, including any variations between building type.

Finance costs
To capture the costs of financing capital and retrofit investments, notional commercial and private (i.e. household) costs of capital were applied to the calculated costs. Retrofit measures were assumed to be paid for over a 10-year period with a private cost of capital of 3.5%, while capital investment in new buildings was assumed to be repaid within 1 year at a commercial cost of capital of 7.5%.

Cost sensitivities
Sensitivity analysis on the housing costs included a spread of +/- 10% for development scale, i.e. an overall range of 20%, and incorporated as spread of +/- 20% of the central cost to account for regional variations in price. This range is representative of BCIS's[65] regional price indices although it does not capture their very low-cost index of 52 for Northern Ireland. The overall range in costs based on location and developer size was therefore 72% to 132% of the central price for domestic costs.

Regional price factors were also included as sensitivities in the non-domestic cost analysis but no adjustment for development scale was included on the basis that for the archetypes under consideration there would be less variation in economies of scale than in the domestic sector.

[64] Element Energy, 2015. Research on district heating and local approaches to heat decarbonisation.
[65] Building Cost Information Services

HM Treasury price deflators were used to adjust 2017 costs to the relevant build year (e.g. 2020, 2025, etc). It should be noted that construction costs can vary considerably and rapidly with market conditions, particularly where activity levels result in a change in the availability of skills and materials. In these situations, it is not unusual to see quite large (several percentage points) change in overall costs over a period of months.

Cost projections

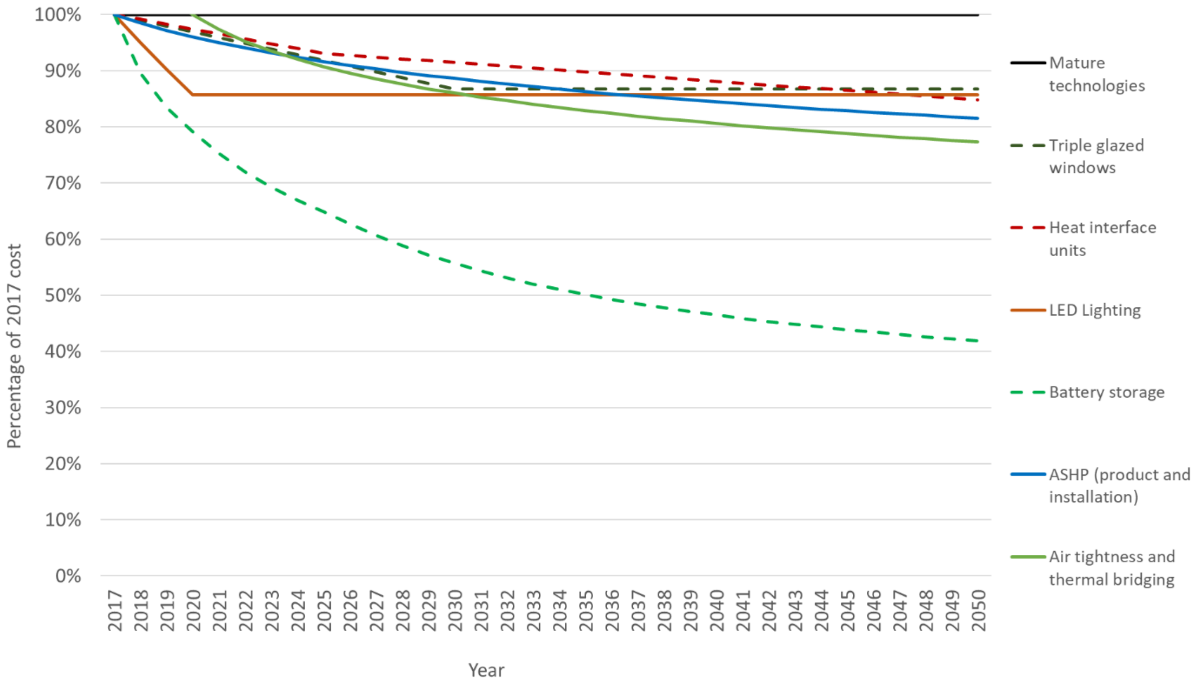
Central, high and low-cost projections were developed for each specification option. Where a technology has been in wide usage for many years it was deemed mature and no further cost reductions were incorporated, for other more recent or less widely adopted specifications the potential for future reductions in cost through learning was assessed.

For several product options consideration was only given to the impact of learning on global pricing of products e.g. on triple glazed windows or heat interface units. In several instances analysis also included the potential for additional UK specific learning associated with the potential for cost reductions in the UK supply chain, particularly through reduced costs of adopting novel construction methods or technologies.

The analysis does not quantitively include analysis of any medium to long term cost savings associated with productivity gains of the sort envisaged by the Construction Sector Deal and the Construction Strategy 2025. Should these savings be realised, then this would have the effect of reducing build costs and the additional costs of more energy efficient and lower-carbon buildings, making the achievement of tighter standards more cost-effective.

Figure 4.6 shows the future cost projections of technologies in support of delivering higher energy efficiency of buildings and reduced carbon emissions. These cost projections are relative to 2017 costs and do not account for other economic and market factors impact costs over this period (e.g. market conditions, interest and exchange rates, skills availability and commodity prices).

Figure 4.6 Projected variation in base costs as a result of learning



Appendix E includes details of the approach, evidence and assumptions underpinning the cost projections for each specification together with the projected % of the 2020 cost used for retrofit and replacement costs through to 2050.

4.5 Replacement and maintenance requirements

The replacement and maintenance costs of different construction elements used in the models' life cycle costing analysis were extracted from the CCC 5th Carbon Budget report, published sources, construction products' suppliers or Currie & Brown internal datasets. Only the elements of lifecycle cost that differentiated from the baseline cost were considered. For example, general repair and decoration costs were excluded from the analysis as these would be common to all options irrespective of energy performance.

Replacement costs were assigned to specific components within a specification and avoided replacements of components that would be longer lived. For example, boiler replacements did not include replacement of a hot water tank or to gas or water supplies. Replacement costs included an additional allowance for the costs of working in an existing property and for disposal of the end of life components.

Appendix D describes the assumed replacement and maintenance intervals and associated cost allowances for each specification.

4.6 Energy costs, prices and carbon factors

Energy prices for electricity and gas were provided by CCC based on their analysis of both retail and long run variable costs for energy. The portion of the unit energy price relating to fixed standing charges was extracted from the source price data to enable a variable per unit cost and fixed standing charge to be used to assess household costs. The standing charge was based on the average standing charge for major (big 6) energy suppliers (£154 per year) and assumed to be apportioned equally between gas and electricity supplies.

In line with the CCC's analytical approach for the fifth carbon budget, different long run variable costs of energy were provided for electricity used for heating, hot water and other consumption (e.g. lighting and unregulated loads) based on the extent to which they represent peak or off-peak consumption, and whether the loads are considered as being capable of being moved from peak to off-peak demand.

For heat supplied by LCHNs it was assumed that retail heat prices would be set at a level enabling a comparable overall cost to those for a traditional gas supply, as is typically the case. Therefore, there was no net impact on occupier's energy costs associated with this heat supply option.

Sensitivity analysis also included the use of high and low-price projections for gas based on government price projections published by BEIS[66].

Current and projected electricity grid carbon emission factors for gas and electricity were provided by the CCC. These factors were then used, together with the relevant efficiency factors for each heating / hot water supply option, to determine the carbon emissions associated with heat supplied via gas or the ASHP. The LCHN option was assumed to use river source heat pumps for 70% of the supplied heat with an efficiency of 400%, the remaining 30% of supplied heat was deemed to be generated by high efficiency gas boilers.

[66] BEIS, 2017. Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal - Data tables 1 to 19: supporting the toolkit and the guidance.

4.7 Calculations

A spreadsheet model was developed to calculate the capital and lifetime costs of constructing each of the building archetypes to different performance levels. This included the implications of the performance level achieved on energy (heat, lighting, pumps and fans) demand, the overall energy consumption and the associated carbon emissions.

Energy demand for each building was predicted using SAP 2012 or SBEM (v5.5) compliant software.

Different construction delivery dates were evaluated ranging 2020 to 2030, in order to capture delayed adoption of modelled energy and carbon performance. The costs of retrofitting to the different performance levels were also calculated for future dates running up to 2045. In all models the price year was set to be equivalent to the year of first construction.

The following modelling results were calculated both in absolute terms and relative to the Part L notional specification with gas heating:

- Capital cost (£ per home, £ per m^2 and percentage impact on construction cost)
- Annualised running costs (£ per home and £ per m^2) - including maintenance and replacement costs and retail energy bills
- Operational regulated energy carbon savings (tCO_2e per home, $kgCO_2e$ per m^2)

The social cost-effectiveness of each energy efficiency and heating system combination was assessed on the basis of present value lifetime costs (capital cost, maintenance and replacement costs and energy costs using the long run variable cost of energy) and associated lifetime carbon savings.

Social cost-effectiveness was determined by comparing the £/tCO_2 costs of packages against a ‘target consistent’ carbon value comparator (weighted in accordance with the timing of carbon savings achieved over the life of the building).[67] Both central and high carbon values were considered.

4.8 Stakeholder engagement

Throughout the project input was sought from a wide range of stakeholders these included:

- Both large and smaller housebuilders and developers including:
  - Members of the HBF and Building Alliance Futures Group (including Crest Nicolson, Barratt Homes, Churchill Retirement Living, Persimmon Homes)
  - Berkeley Group
  - Hastoe Homes
  - Melius Homes
  - Lendlease
  - Landsec
- Product suppliers and trade bodies
  - NIBE
  - Baxi Heating
  - Kensa Heat Pumps

[67] i.e. with increasing carbon savings over time for options involving use of electric heating, reflecting the increasing decarbonisation of the electricity system

  - Grundfos
  - Heatrae Sadia
  - Nilan
  - Viessmann
  - Sustainable Energy Association
  - Spirit Energy
  - Kingspan
  - Aerogel UK
  - Aereco
  - H+H
  - Ibstock

- Architects and consultants – designers of low energy housing were interviewed to understand the techniques, design solutions and practical challenges involved

  - Architype
  - Gale & Snowden
  - Twin Sustainability Innovation
  - Etude
  - AA Projects
  - Elementa
  - Buro Happold
  - Pollard Thomas Edwards

- Policy makers and advisors

  - UK Green Building Council
  - Sustainable Energy Association
  - Greater London Authority
  - Department for Business Energy and Industrial Strategy
  - Ministry of Housing, Communities and Local Government

MODELLING RESULTS

5. Domestic

Modelling results are shown for the domestic archetypes including:

- Build costs
  - Impact on capital costs compared to the Part L 2013 notional specification
  - Projected capital cost impact between 2020 and 2030
  - Retrofit costs in a 2030 retrofit year
  - Comparative costs of different standards when delivered as new build or via subsequent retrofit
- Lifetime costs
  - Including impact on present value build costs, replacement and maintenance costs, energy costs (using long run variable cost of energy) in 2020
  - Annualised household cost (including replacement, maintenance and retail energy costs) against capital cost
- Social cost-effectiveness and carbon savings
  - Trends in cost-effectiveness reflecting both changes in present value lifetime costs and in the comparative average carbon value for homes built between 2020 and 2030.
  - Carbon savings against present value lifetime costs and by comparison to the CCC's average carbon value over the life of the home, weighted by discounted carbon abatement in each year.
- Sensitivity analyses
  - Analysis of the implications of a range of sensitivity tests on the results covering construction costs, energy prices and assumed efficiency of heat pumps

All results are shown for the semi-detached house, Appendix F contains results of the cost-effectiveness analysis for each of the other domestic archetypes.

Table 5.1 summarises the descriptions used to define each combination of energy efficiency level and heating source in the subsequent results.

Table 5.1 Description of combined space heating energy efficiency and heating source options

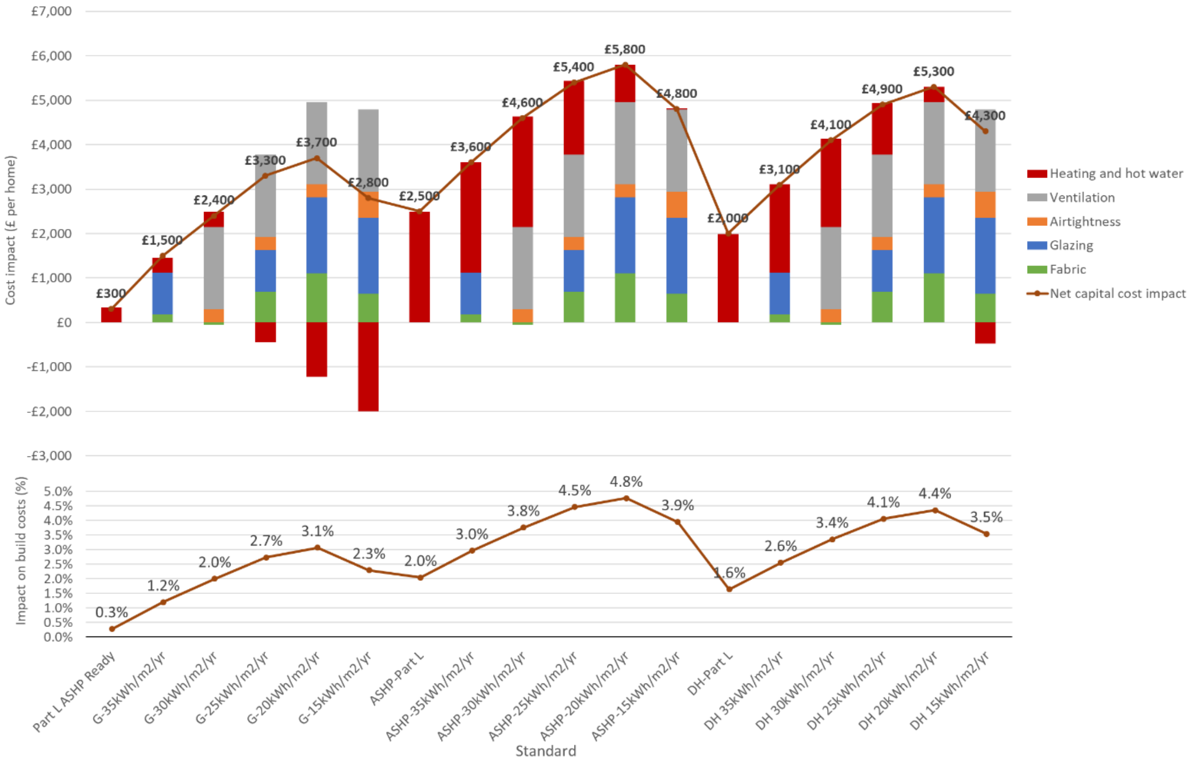
Space Heating Demand	Heat Source		
	Gas Boiler	ASHP	LCHN
Part L notional specification	*G-Part L Notional*	*ASHP-Part L*	*DH-Part L*
Part L - ASHP Ready*	*Part L – ASHP Ready*		
35 kWh/m²/yr	*G-35kWh/m²/yr*	*ASHP-35kWh/m²/yr*	*DH 35kWh/m²/yr*
30 kWh/m²/yr	*G-30kWh/m²/yr*	*ASHP-30kWh/m²/yr*	*DH 30kWh/m²/yr*
25 kWh/m²/yr	*G-25kWh/m²/yr*	*ASHP-25kWh/m²/yr*	*DH 25kWh/m²/yr*
20 kWh/m²/yr	*G-20kWh/m²/yr*	*ASHP-20kWh/m²/yr*	*DH 20kWh/m²/yr*
15 kWh/m²/yr	*G-15kWh/m²/yr*	*ASHP-15kWh/m²/yr*	*DH 15kWh/m²/yr*

* An amended version of the Part L notional specification that includes larger radiators capable of working with a lower temperature heating system such as that provided by an ASHP or modern LCHN.

5.1 New build capital costs in 2020

Figures 5.1 to 5.4 show the additional capital costs for each dwelling type of achieving varying space heating demands in combination with different heating systems in 2020. The Part L 2013 notional specification is used as the baseline from which cost variances are assessed. Appendix F shows the cost uplift associated with a high cost scenario for the semi-detached house.

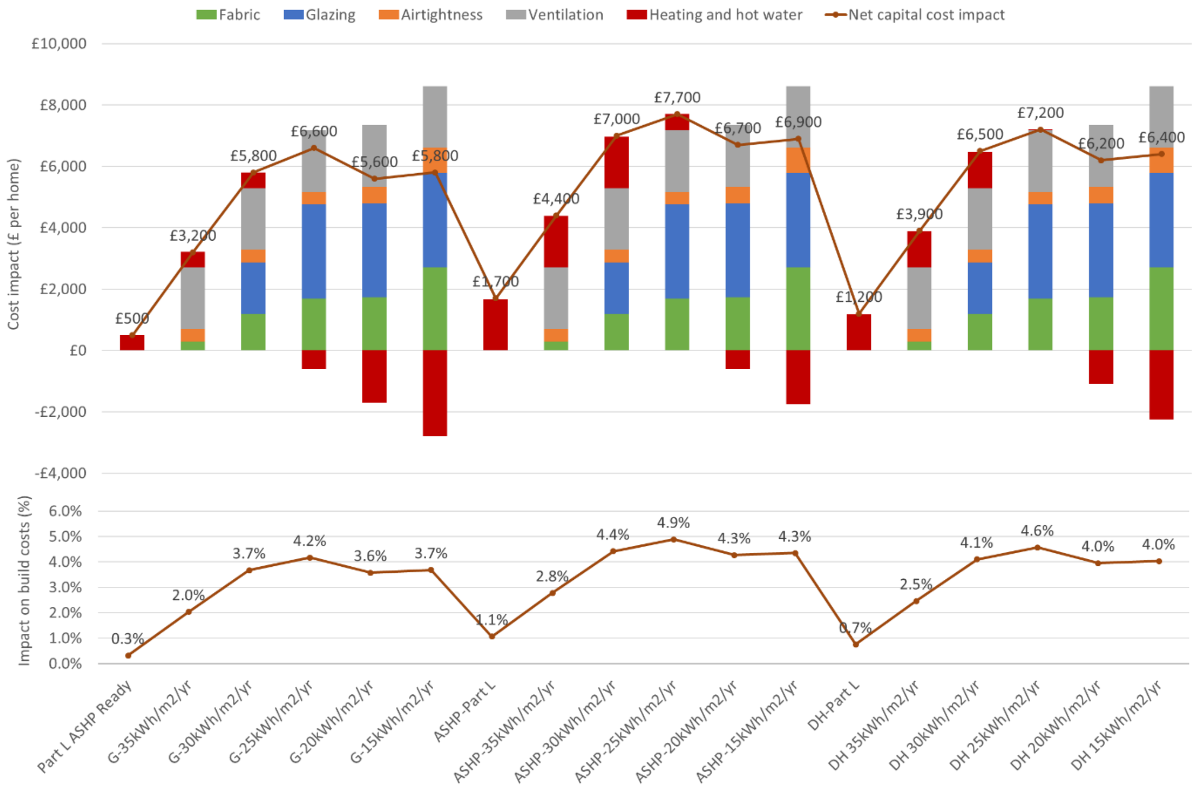
Figure 5.1 Additional capital costs of reducing space heating demand in combination with different heating systems – semi-detached house in 2020



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.
- 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.

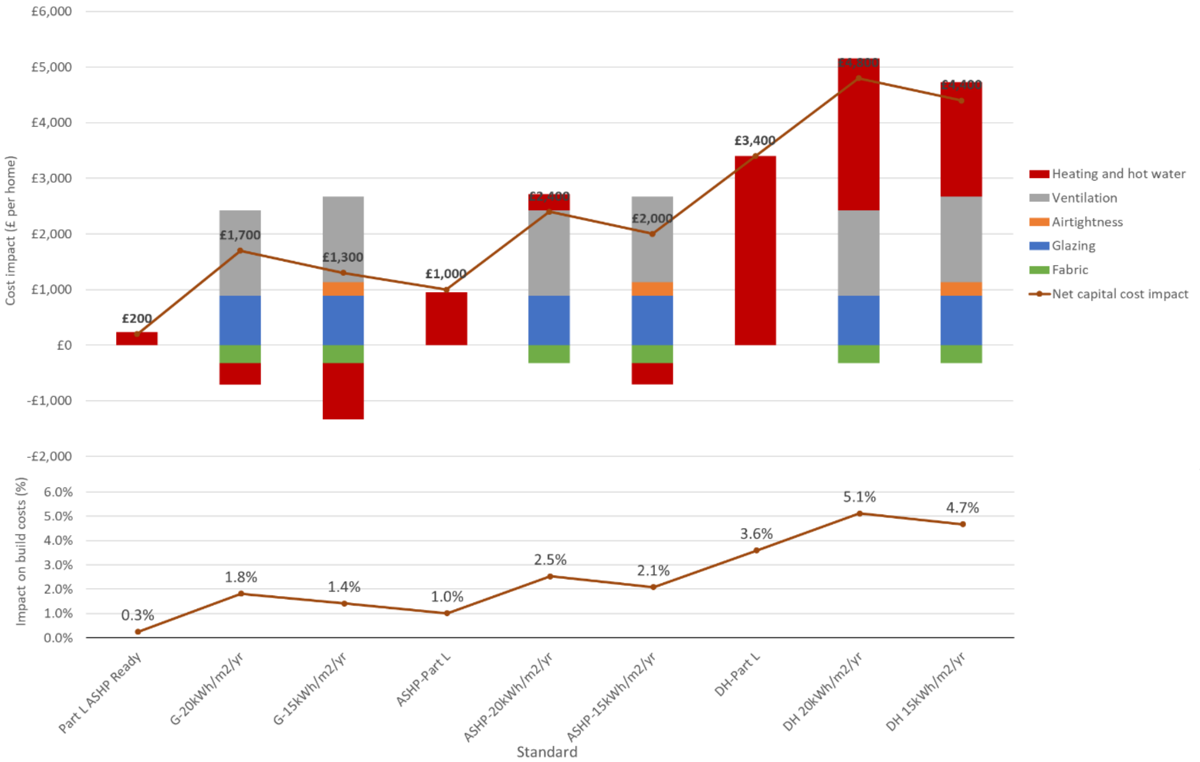
Figure 5.2 Additional capital costs of reducing space heating demand in combination with different heating systems – detached house in 2020



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/m^2/yr in a detached house it is necessary to have external wall U values of 0.13 W/m^2 K even with an air tightness of 1m^3m^2hr; in a semi-detached house with equivalent airtightness it is possible to achieve this standard with a wall U value of 0.21 W/m^2 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.

Figure 5.3 Additional capital costs of reducing space heating demand in combination with different heating systems – large (low rise) flat in 2020

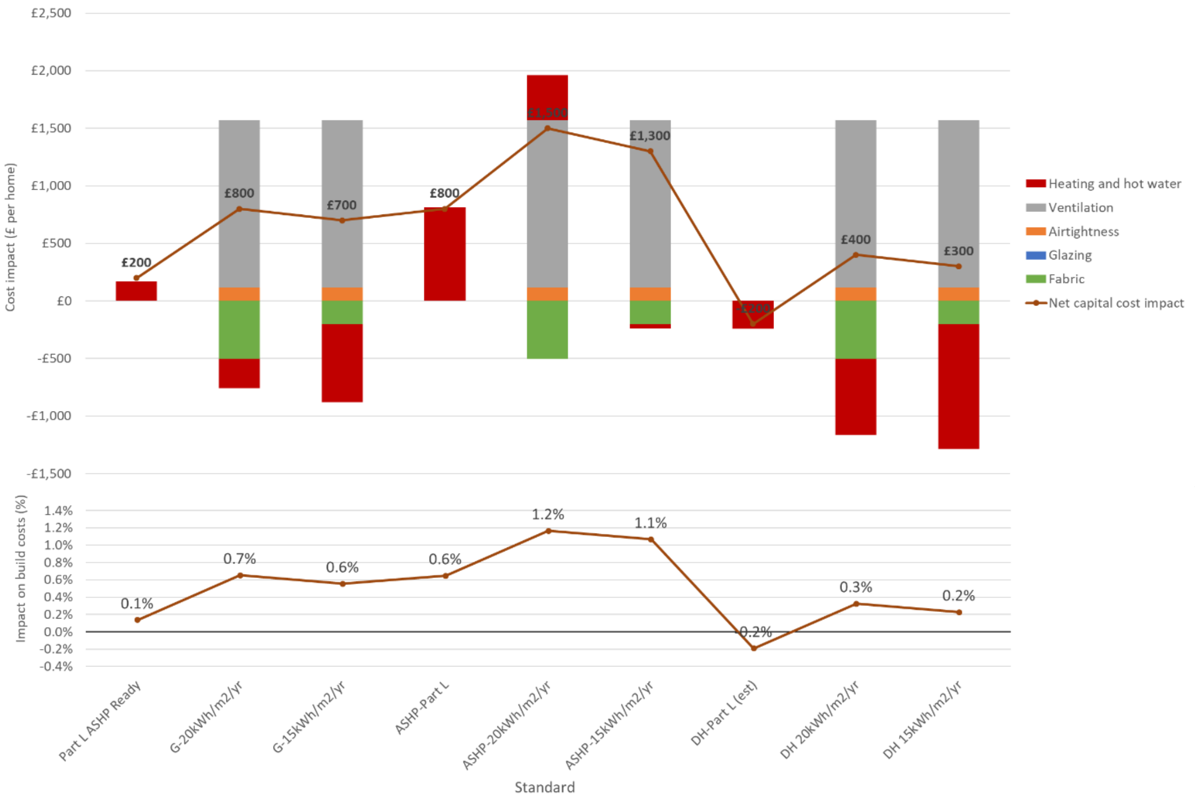


Key findings:

- 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/m^2/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[68] - 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.

[68] Aqua Consultants for the CCC, as part of Frontier Economics and Aqua Consultants (2016) Future Regulation of the UK Gas Grid, Impacts and Institutional implications of UK gas grid future scenarios.

Figure 5.4 Additional capital costs of reducing space heating demand in combination with different heating systems – small (high rise) flat in 2020

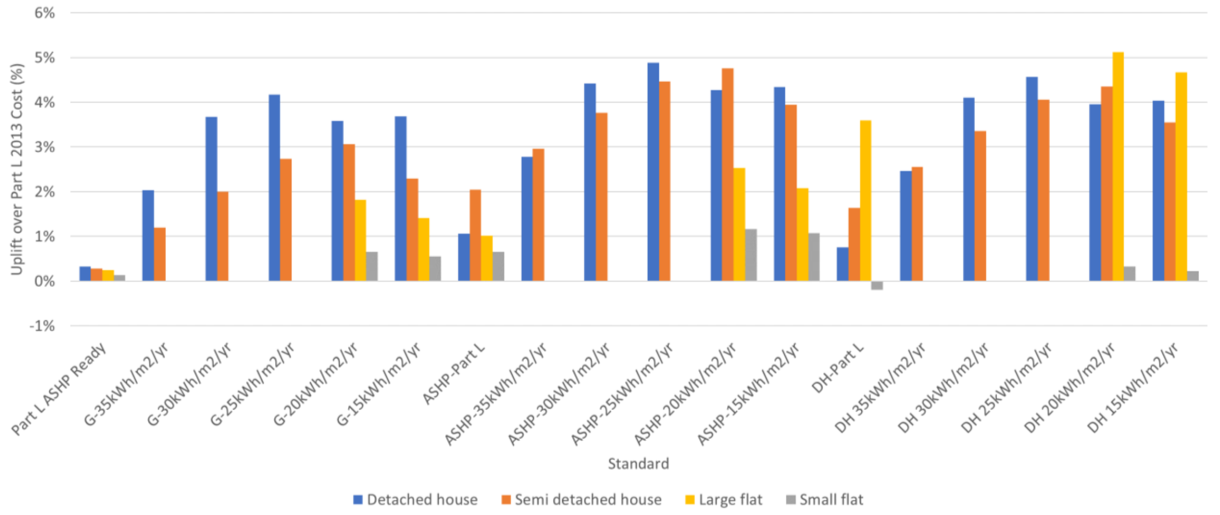


Key findings:

- 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/m^2/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/m^2/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.

Figure 5.5 summarises the percentage cost uplifts for each dwelling type. For the LCHN options the cost uplifts exclude the costs of the network and are limited to systems within the development, i.e. central and dwelling specific heat interface units and associated distribution stems and pumps together with a short network connection.

Figure 5.5 Additional capital costs of reducing space heating demand in combination with different heating systems for each dwelling type in 2020



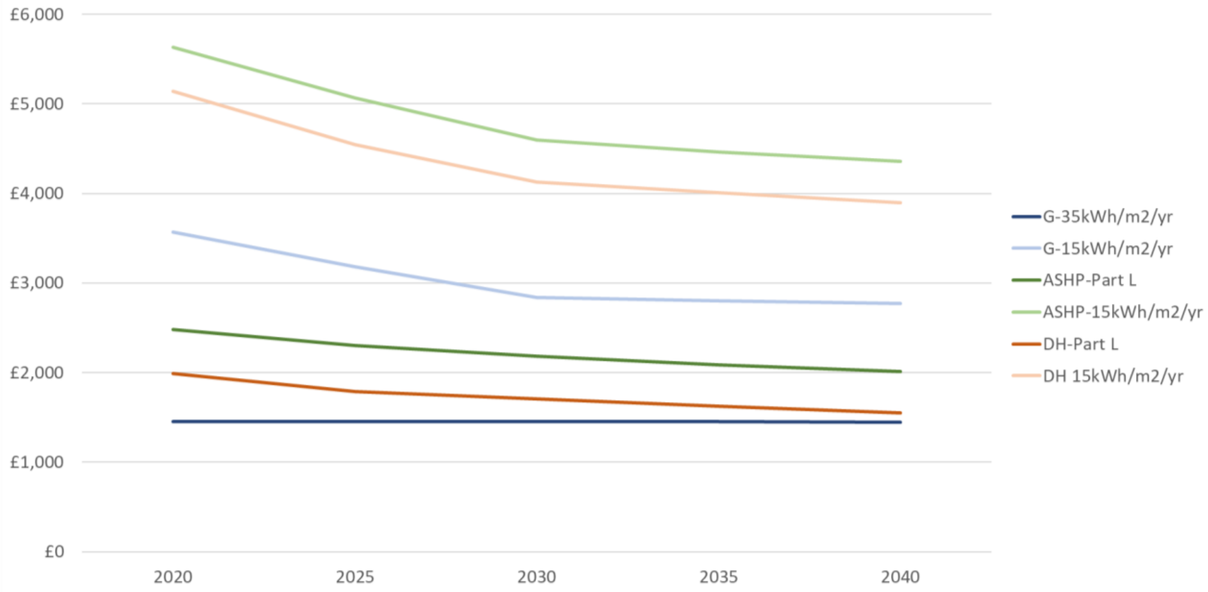
Key findings:

- In each case the uplift cost of achieving the enhanced space heating and/or low-carbon heating combination is around 5% or less.
- The additional costs of tighter space heating standards are higher for less efficient building forms (i.e. those with more external area relative to their internal area). Costs are highest for detached houses followed by semi-detached houses, large flats and small flats.
- The costs of adding an ASHP are higher for semi-detached homes than for detached houses, because of the need to add a hot water store that would not otherwise be specified.
- The costs of connecting to a LCHN are higher for large flats because of the additional costs involved in adopting a centralised block level heating distribution system with associated pumps and heat interface units. These are not additional costs for the high-rise flat option which would have these systems in place for all options.

5.2 New build capital costs - period 2020 to 2040

Figure 5.6 shows the predicted capital cost increase of building a semi-detached house to higher standards and with the use of low-carbon heat for construction in the years between 2020 and 2040.

Figure 5.6 Projected trend in the additional capital costs of building to higher standards overtime – semi detached house



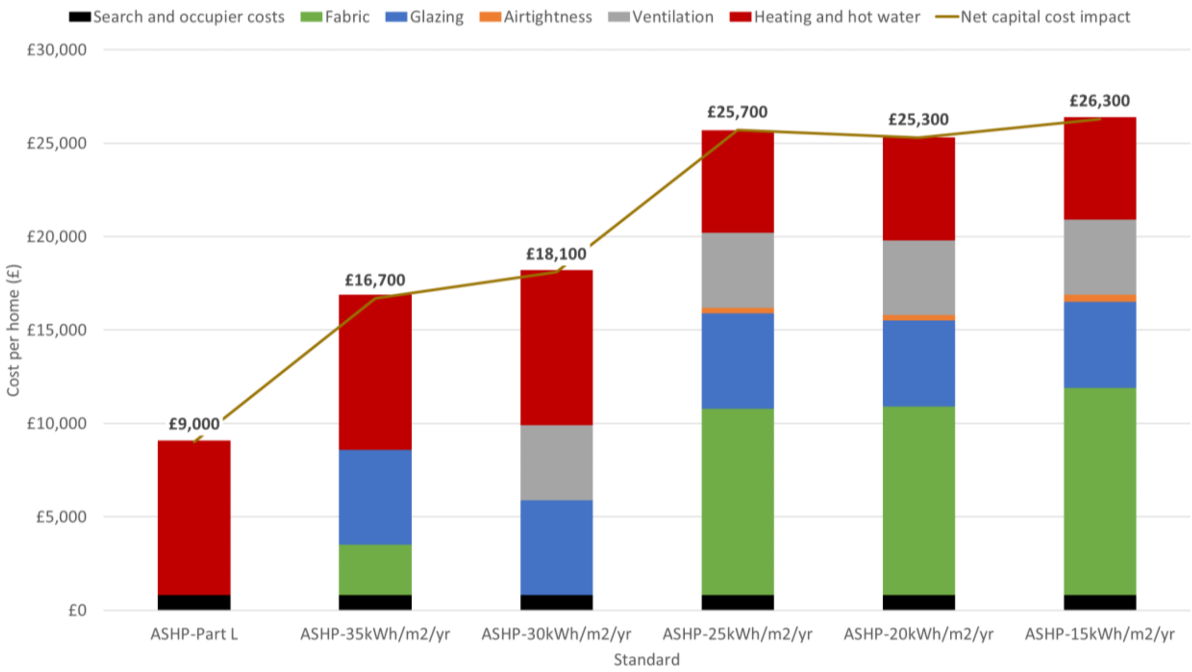
Key findings:

- The relative cost of tighter standards and/ or adopting low-carbon heat reduce over time for most options. This is a result of reductions in the cost of improving airtightness and in the costs of high-performance windows and to a lesser extent the cost of ASHP installation which is projected to reduce in nominal cost by 4-5% between 2020 and 2025.
- Cost reductions over time are more substantial for those dwellings with low space heating demand albeit these are higher in 2020. This is because these additional costs include for higher airtightness and glazing standards both of which are subject to more rapid cost reductions over time. The glazing cost premium is projected to reduce because the additional material costs of triple glazed units falls over time, while for airtightness both the labour and material costs of achieving higher airtightness decline over time.

5.3 Retrofit costs

Figure 5.7 shows the cost of achieving space heating demand and heating system standards as a retrofit to a home originally built to the Part L 2013 notional specification.

Figure 5.7 Capital cost of retrofitting to higher space heating standards with an ASHP (nominal undiscounted cost in 2030)



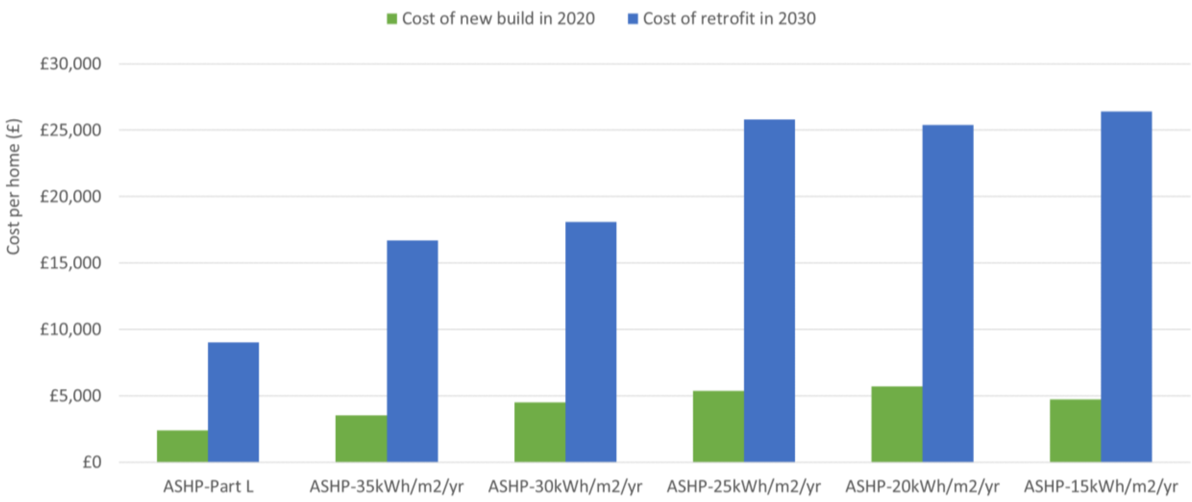
Key findings:

- The estimated retrofit cost for each option even when involving a relatively small reduction in space heating demand is significant, ranging from around £16,700 to over £26,000 to achieve the 15kWh/m^2/yr standard[69]. These costs also include an allowance for home occupiers hidden costs, for example in commissioning surveys, identifying contractors to undertake the works, and managing the associated disruption[70]. Nonetheless the perceived 'hassle' associated with the process is likely to be an additional unmonetised barrier for many households.
- The costs of retrofitting a heat pump are with no additional efficiency measures are around £9,000 this includes search and occupier costs, the cost of the pump and installation sundries, installation of a new hot water store and replacement existing radiators with those capable of providing sufficient output at a low operating temperature. Radiator replacement is assumed to have some impact on the associated hot water distribution pipes and require an element of making good the affected walls.

[69] To keep the retrofit costs as low as possible in these scenarios, retrofit to flooring (to go from a U value of 0.13 to 0.11 Wm^{2}K) was omitted. The impact on overall space heating demand from omitting this measure was negligible, but the cost saving was over £8,000 for the semi-detached house.
[70] Hidden costs were derived from those identified in Ecofys, 2009. The hidden costs and benefits of domestic energy efficiency and carbon saving measures. A report for the Department for Energy and Climate Change.

Figure 5.8 compares retrofit costs of the different modelled performance scenarios to achieving the same standards in new build as shown in Figure 5.1.

Figure 5.8 Additional cost of installing ASHP and meeting space heating standards in a new semi-detached house or via retrofit[71]



Key findings:

- The costs of achieving higher standards via retrofit are between three and more than five times higher than during construction
- In addition to the substantial costs associated with these retrofit options, there are questions over the feasibility of generating significant uptake of retrofit measures within relatively newly built homes, given the challenges that have been experienced securing uptake of domestic retrofit programmes for much less efficient older homes.
- The substantially lower cost and far higher deliverability of reducing space heating demand during new build rather than retrofit activities indicates that if there is a case to tighten space heating standards to meet UK's climate change targets then this should be addressed in the construction of the homes.
- The introduction of low-carbon heat is substantially lower cost if installed as part of the construction process rather than as a retrofit measure, for a semi-detached house this difference is around £6,700 in nominal prices or £5,600 in comparable 2020 present values.

5.4 Enabling efficient retrofit of low-carbon heating

Achieving the UK's climate change targets requires the almost complete decarbonisation of heat in buildings. Therefore, is important that any new homes that do not have low-carbon heat systems when constructed are able to retrofit to this technology efficiently. A key measure to enable the adoption of most low-carbon heat systems is the ability to utilise low temperature heat such as that supplied by modern heat networks and by heat pumps.

Analysis of ASHP retrofit identified two substantial costs associated with the retrofit of low-carbon heat in a new gas heated home that could be cost-effectively avoided through changes in the new build specification. These comprised installation of:

[71] Nominal undiscounted costs in 2020 / 2030 respectively.

- Radiators capable of delivering enough heat when operated at the lower temperatures that would enable heat pumps and heat networks to run most efficiently. These would need to have approximately 2.5 the heat output of the minimum[72] radiator size used by a higher temperature system such as a gas boiler. To achieve the higher heat output the radiator would need to be larger and/or accommodate double or even triple radiant panels to increase heat output. The additional cost of radiators with higher heat outputs (c.£30 per radiator) is an increase of around 50% in the cost of the radiator unit. However, this is a much smaller proportion (12%) of the total installation costs which are c.£240 per radiator, as all the associated pipework, fittings and installation costs are comparable.
- Hot water stores that are capable of operating at lower temperatures in homes where hot water stores are installed (the detached house in this study). To be compatible with a heat pump a hot water store needs to contain a larger heat exchange surface but is otherwise largely equivalent in specification and price to that used with a traditional gas boiler.

The installation of radiators with a higher heat output in a new home would add around £150-£500 to the cost of building a home but these would not need to be replaced if a low temperature, low-carbon heat source was subsequently installed as a retrofit. As well as reducing the retrofit costs, the ability to retain existing radiators would avoid the associated disruption within rooms, which could be considerable in some situations, and any adjustments to hot water distribution pipes.

The installation of low temperature compatible radiators in a new home would result in real cost savings of retrofitting an ASHP of approximately £1,500-£5,500 depending on the archetype.

A further benefit from installing radiators capable of operating at lower temperatures in a new home is that they would enable the gas boiler to operate more efficiently (by approximately 3%) thereby reducing operational energy use and carbon emissions in the years prior to the installation of a heat pump.

5.5 Addition of measures to provide demand flexibility and provide shading

The role of technologies to enable some flexibility in the timing of energy consumption were considered including the use of battery and thermal storage to shift energy demand from peak periods to off peak. Costs for installing a 2kWh battery system were estimated at c.£2,000 in 2018 and projected to reduce to around £1,600 by 2020. The provision of sufficient heating water storage (i.e. via a thermal store) to enable 90% of heating energy demand to be shifted to off peak consumption was estimated[73] for each house type and space heating demand level, with costs ranging from around £4,300 for a detached house at the Part L specification down to c.£1,600 for a small flat with space heat demand of 15kWh/m^2/yr.

The cost effectiveness of these demand flexibility measures was not considered in detail as the relationship between demand flexibility and marginal carbon emissions and the levels of thermal

[72] It may be the case that radiators in new homes are already above this minimum size to provide a safety margin.

[73] Without more detailed information on heating response patterns in each house type (which is not available in SAP) the level of thermal storage to enable heat shifting was estimated based on adjustment of previous analysis of existing buildings. Further, more detailed modelling on thermal inertia in homes of different efficiency levels, the size of thermal storage and potential for integration within domestic hot water storage is recommended to further develop this analysis.

inertia in homes built to differing fabric specifications could not be defined with sufficient confidence.

Costs associated with external shading were also estimated as one of a variety of measures that could be applied to address overheating risk. The analysis identified that external blinds, for example, in a new flat would cost c.£650 per flat, whereas if installed as a retrofit, costs could be £3,600 or higher[74], if the retrofit required refitting windows so that they could be opened when shading is in place. Ensuring that windows can be opened when combined with an external shading solution would help reduce the risk of unnecessary window replacements with associated cost and wastage. Further work on climate adaptation measures is included in separate reports produced for the CCC[75].

5.6 Lifetime and running costs

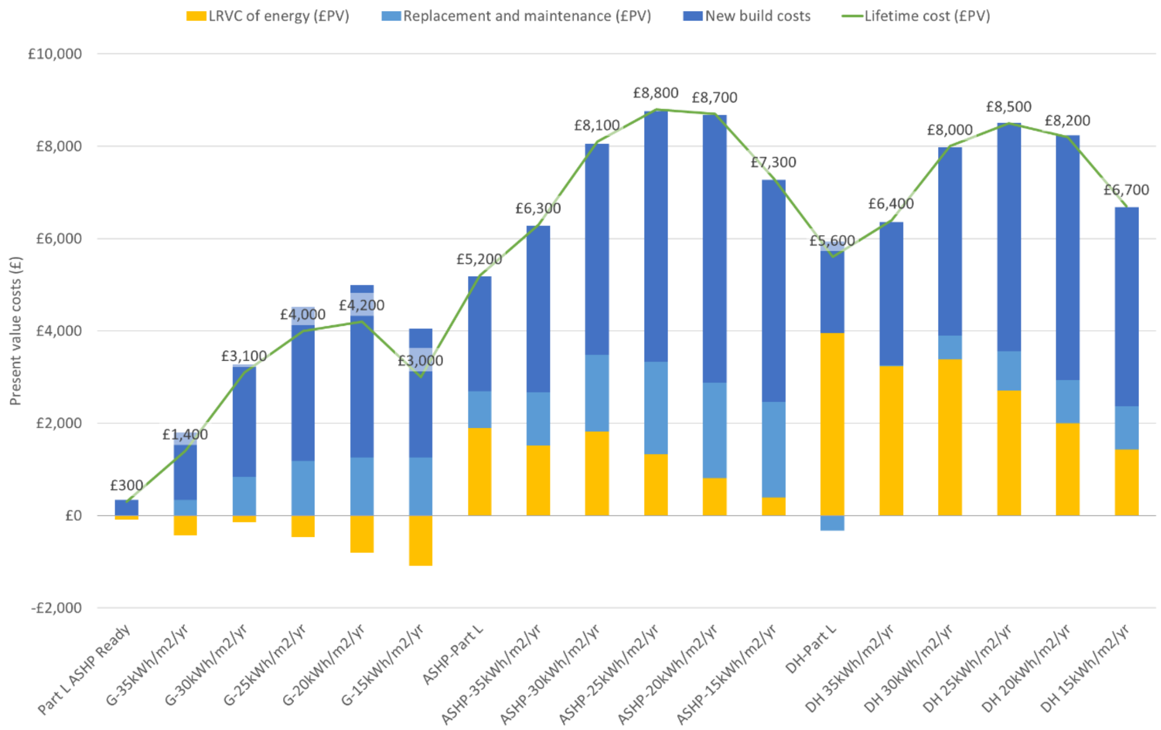
The effect of tighter standards and low-carbon heat on running and lifetime costs are significant influences on the cost-effectiveness of different packages of measures and are also an important standalone consideration, in light of concerns over energy costs and fuel poverty.

From a social perspective, lifetime costs include the capital cost, replacement and maintenance costs over a 60-year[76] lifespan together with the long run variable cost of the energy used. The long run variable cost of energy captures the societal costs of supplying energy including generation, transmission and distribution but does not include carbon or other taxes or supplier profits.

Figure 5.9 shows the impact on estimated lifetime costs for each of the heating and space heat demand combinations considered for the assessed semi-detached house.

[74] Depending on costs of access and any associated impact on windows/façade system.
[75] Wood Plc et al. for the CCC (2019) Updating an assessment of the costs and benefits of low-regret climate change adaptation options in the residential buildings sector
[76] A lifespan of 60 years is consistent with that typically used in the impact assessment of building regulations although many elements of the construction would be expected to have a longer lifespan in practice.

Figure 5.9 Impact on lifetime costs of different heating system and space heating standards in a semi-detached house built in 2020

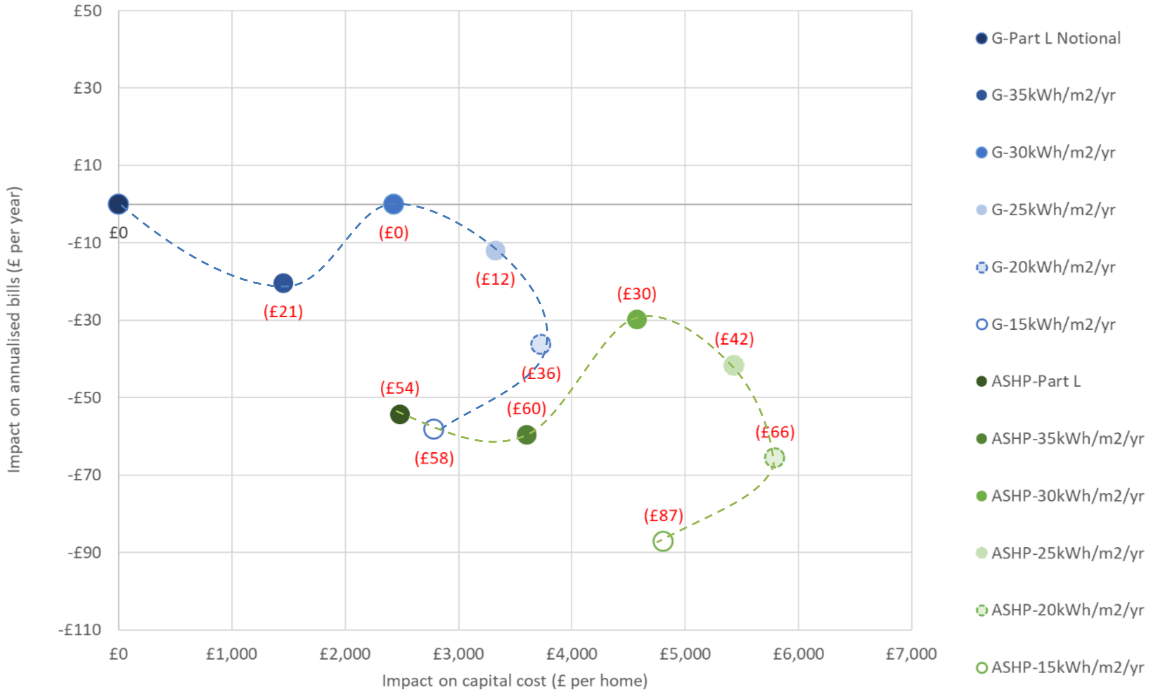


Key findings:

- None of the scenarios represent an overall lifetime cost saving, in the absence of considering the value of the carbon saved.
- For gas and ASHP heated homes at all tighter standards, the lifetime costs are dominated by capital costs.
- For homes connected to a LCHN the energy costs dominate: this is because these costs are based on the levelised costs of energy (LCOE) for the network (assuming a high heat density). This LCOE therefore includes a contribution to the capital costs of the network as well as the costs of supplying the heat.
- The specifications with lower space heating demand have increased maintenance and replacement costs compared to the Part L notional specification because the of the additional costs of replacing triple glazed windows (after 30 years) and MVHR systems (after 20 years) together with a £25 per year allowance for replacement MVHR filters.

To examine the relationship between build costs and household running costs, Figures 5.10 and 5.11 show the estimated annualised running costs in 2020 and 2025 of the gas and ASHP heated homes built to different space heating demand levels set against their relative capital cost.

Figure 5.10 Relative running and capital costs for a semi-detached house with different heating systems[77] and space heating demand in 2020

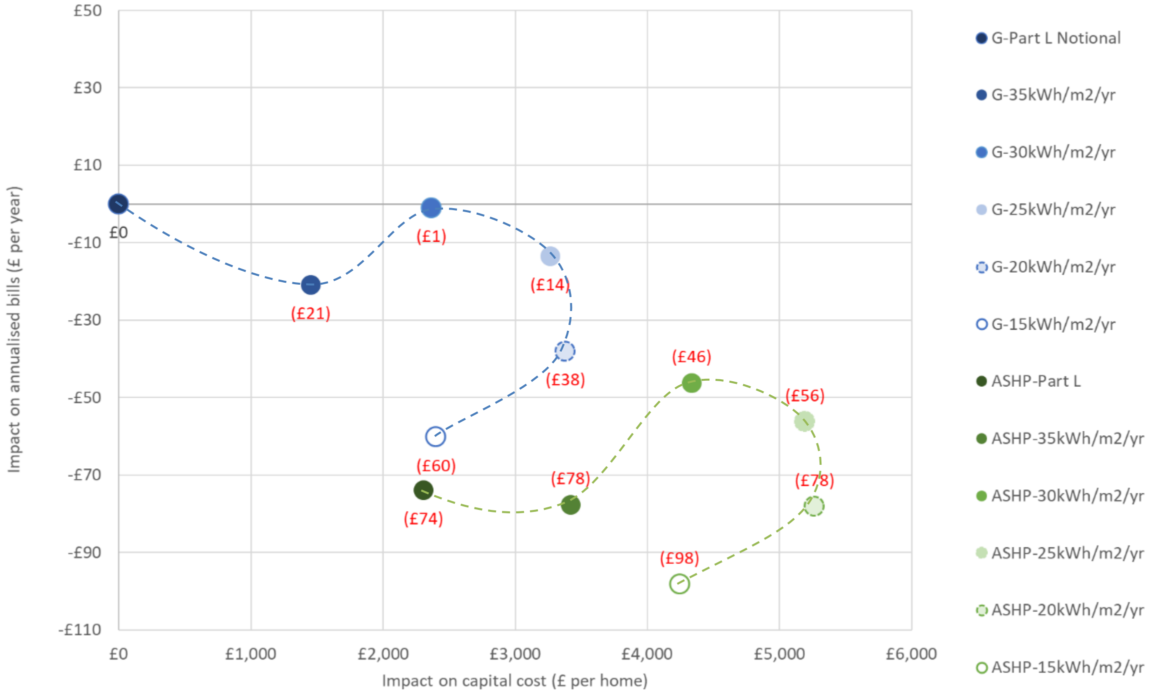


Key findings:

- 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.
- Over their lifetime, homes with low-carbon heat based on an ASHP can deliver lower annualised running costs than a conventional gas boiler. This is because of the increased lifespan of ASHP compared to gas boilers which reduces replacement costs, and the reductions in energy costs which principally arise after 2040. Energy costs in 2020 may be around £22 per year higher with an ASHP than a gas boiler for a home of the same space heating but this is outweighed by the £77 saving in annual standing charge that is avoided for homes without a gas supply.
- Higher capital costs deliver lower energy costs for households but for 'intermediate specifications', i.e. those that are better than the current Part L but not at ultra-high standards such as 15kWh/m^2/yr, the higher capital costs can deliver little or no saving in the estimated running costs. This is because the energy and maintenance costs of MVHR systems are more than the resulting reduction in heating costs where fabric and airtightness levels are insufficient. An important finding is therefore that if MVHR systems are utilised they should be combined with enough improvement in space heating demand to ensure that the savings in heating costs outweigh the cost of running their fans and of changing filters when needed.

[77] The running costs of LCHN are not considered in this analysis as albeit running costs may be similar to those for gas heated homes where there is a commitment by suppliers to peg prices to a gas heating comparator, where this is the case it would be expected that the developer would need to make an additional capital contribution on connecting to the network.

Figure 5.11 Relative running and capital costs for a semi-detached house with different heating systems and space heating demand in 2025



Key findings:

- For homes built in 2025, the pattern of running and capital costs is broadly similar to that in 2020 but the annualised running costs are lower than previously as a result of the CCC's projections for a reduction in retail electricity costs after 2030.

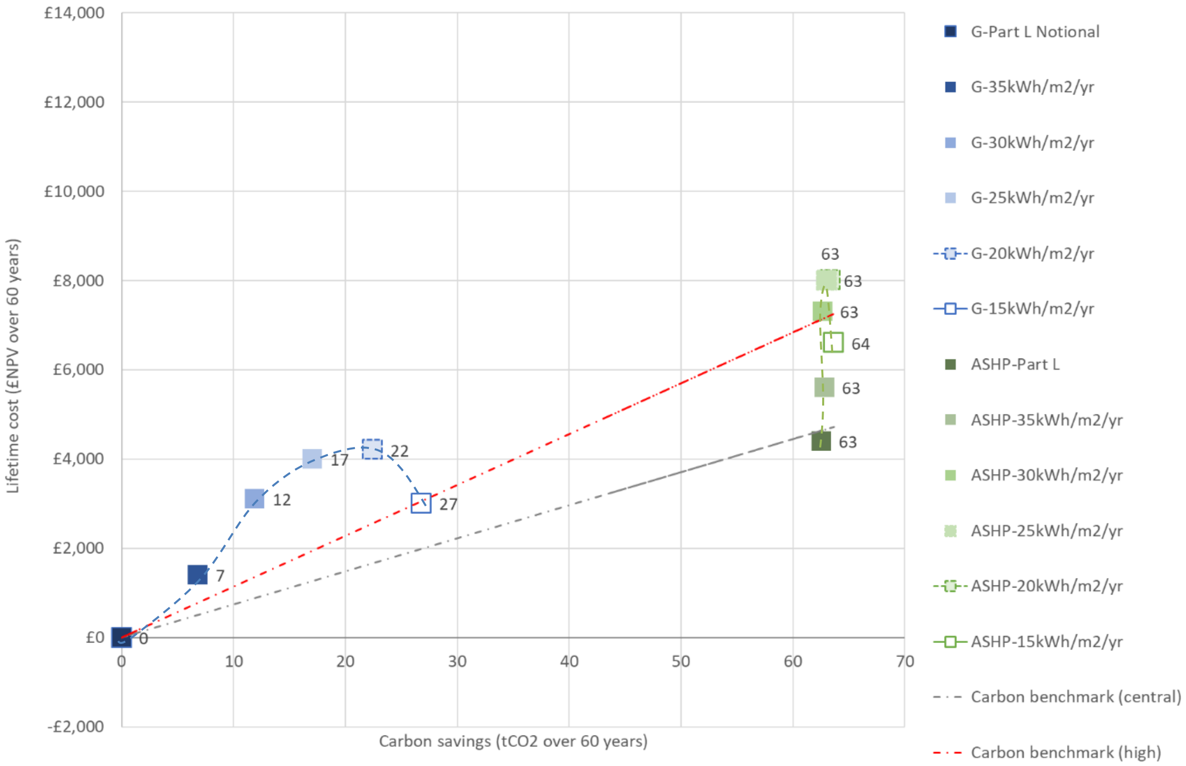
5.7 Cost-effectiveness

Figures 5.12 and 5.13 show the carbon savings and lifetime costs of homes built in 2021 and 2025 with gas and ASHP heating and to different space heating standards. On each chart two lines show the price of an equivalent carbon saving based on the CCC's discounted weighted[78] price of carbon over the 60-year lifetime of the home, with the lower line representing central carbon values, and the higher line representing high carbon values.

Typically, measures are deemed cost-effective under the CCC's Central Scenarios, when they compare favourably against central carbon values. However, special interest is placed on the high carbon value trajectory in light of prospective developments in favour of more ambitious long-term carbon targets.

[78] I.e. carbon value is weighted according to the quantity of emission reductions that arise in each year. In these examples, emission reductions are proportionately higher in the early years of the home's operation. The annual emissions for all scenarios reduce over time as grid decarbonisation reduces the carbon impact of electricity consumption.

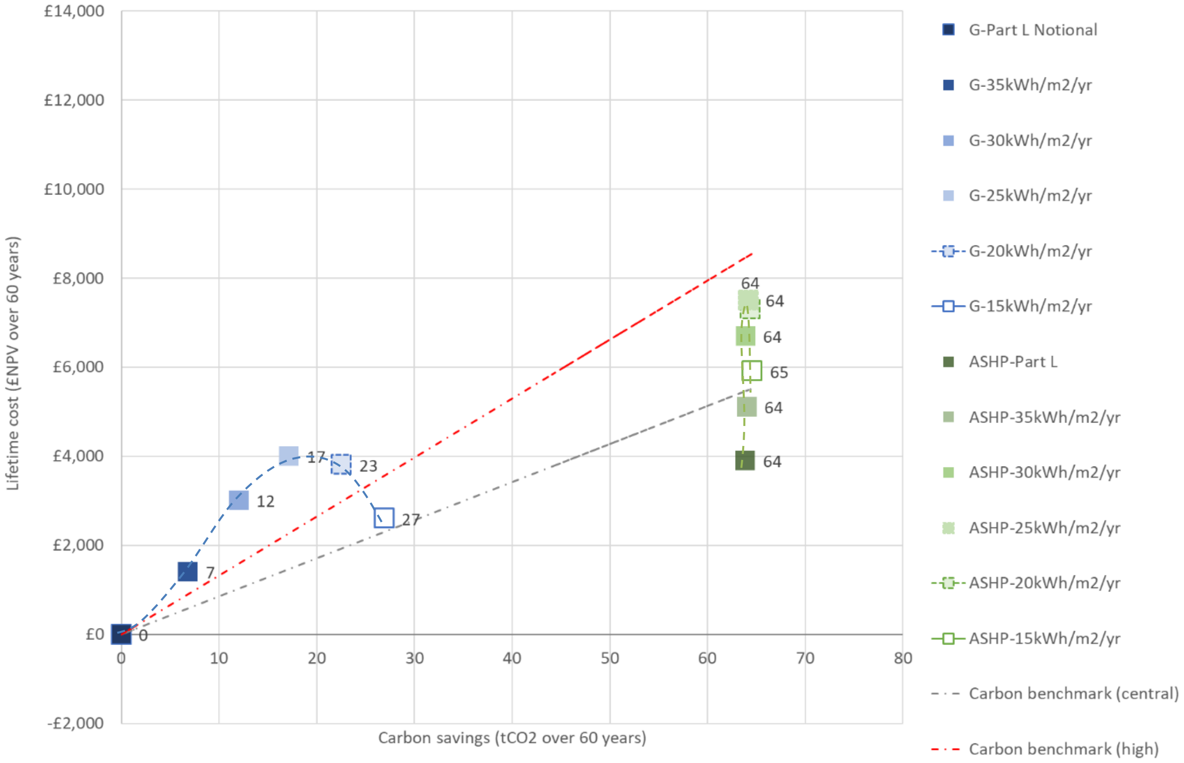
Figure 5.12 Carbon savings and lifetime costs of semi-detached house with different heating systems and space heating demand in 2021



Key findings:

- By 2021 all Part L homes with low-carbon heat via an ASHP become cost-effective against the central carbon value, and homes with a space heat demand of 15kWh/m^2/yr and an ASHP are cost-effective against a high carbon value.
- The lifetime operational carbon savings associated with low-carbon heat are significantly greater (over double) those arising from reducing space heating demand but retaining a gas boiler.
- Once an ASHP is installed the additional lifetime operational carbon savings from tighter space heating standards (even to the ultra-high efficiency standard of 15kWh/m^2/yr) are small. However, tighter standards can reduce energy use, running costs (see Section 5.5) and also levels of peak energy demand.

Figure 5.13 Carbon savings and lifetime costs of semi-detached house with different heating systems and space heating demand in 2025



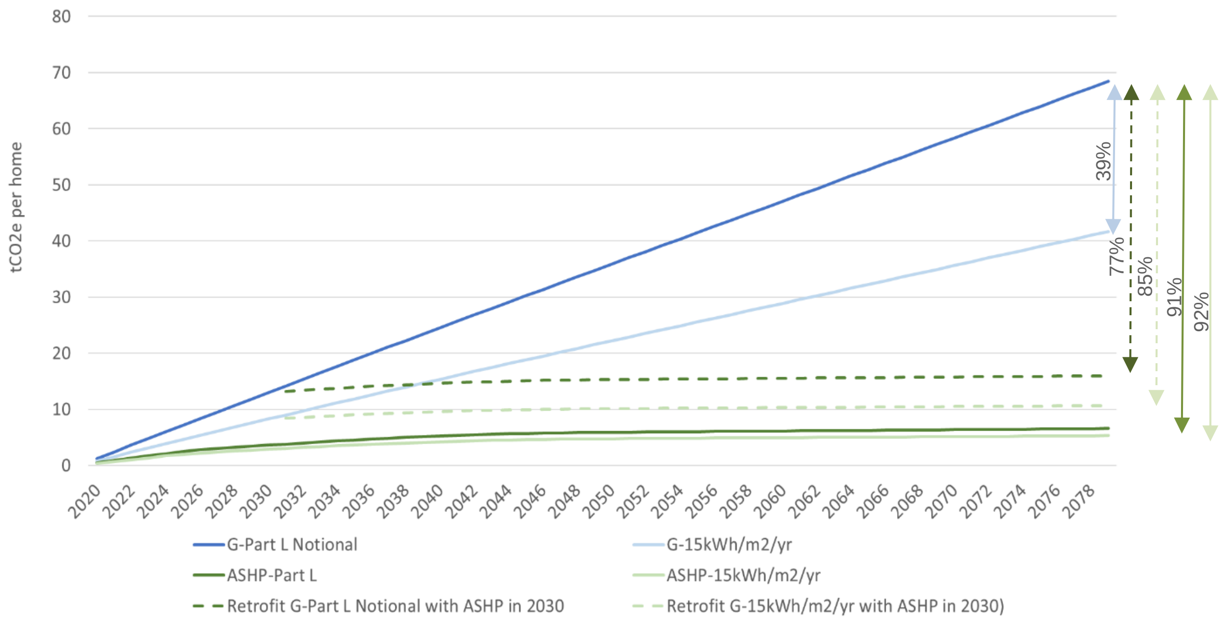
Key findings:

- By 2025, low-carbon heat and a space heat demand of 15kWh/m^2/yr are cost-effective (£92 per tCO_2e) across almost all archetypes at central carbon values. The exception is the semi-detached house (Figure 5.13) where this combination of measures becomes cost-effective again the central carbon value by 2027. In 2025 this package of measures is cost-effective across all archetypes at high carbon values. Findings for other house types are set out in Appendix F.
- For the gas heated homes, the cost effectiveness of the ultra-high efficiency standard varies considerably by house type. For a semi-detached home the 15kWh/m^2/yr standard is cost-effective against the high carbon value by 2025 and against the central price by 2028. However, for the detached house the costs of achieving this standard are higher and although also cost effective in 2025 against the high carbon value, these specifications are not cost effective compared to a central carbon value until after 2030. In flats, although the additional costs of meeting the 15kWh/m^2/yr standard are smaller than for housing the level of additional gas saving is also far smaller than for the houses. As a result, ultra-high efficiency standards are not cost effective against a central carbon value for gas heated flats until after 2030.

5.8 Carbon savings

Figure 5.14 shows the cumulative carbon savings of a semi-detached house heated with either gas boilers or an ASHP built to either the Part L 2013 Notional or space heating demand standard of 15kWh/m^2/yr in 2020. The impact of the retrofit of an ASHP into a gas heated home in 2030 on cumulative lifetime carbon emissions is also shown.

Figure 5.14 Cumulative carbon emissions from a semi-detached house built to different space heating demand standards with either a gas boiler or ASHP, including retrofit of ASHP after 10 years



Key findings:

- The use of an ASHP to provide low-carbon heat results in very substantial (91-92%) carbon savings even when compared to a home built to current regulatory minima and also demonstrates significant additional savings (over double) when compared to a home with a very low space heating demand of 15kWh/m^2/yr when heated is provided by a gas boiler.
- With an ASHP, there is relatively little difference in lifetime carbon emissions between different space heating specifications whereas with gas heating the specification with lower space heating has nearly 40% lower lifetime carbon emissions.
- Even if a gas heated home is retrofitted with a heat pump in the future after only 10 years[79], the carbon penalty for delaying the transition is considerable.
  - For a semi-detached home built to the current Part L Notional specification, replacement of the gas boiler with an ASHP after 10 years would result in lifetime carbon emission that are nearly 10 tonnes per home higher than would be the case if the ASHP had been installed at the outset if the replacement were delayed until the end of life of the boiler then the difference might be 15 tonnes or higher.
  - For a semi-detached home built to an ultra-efficient energy standard, the carbon penalty for delaying the installation of an ASHP is around 5-6 tonnes if the replacement happens after 10 years (more than 3 times higher than a home built with an air source heat pump at the outset) or nearly 10 tonnes per home if delayed until year 15.

[79] Gas boilers would be expected to last for at 15 years or more and there would be no immediate benefit to a household that might persuade them to incur the cost of retrofitting to an ASHP if the boiler were still operational.

5.9 Sensitivity analyses

A range of sensitivity analyses were carried out on the results to test the significance of various assumptions. These analyses are presented in Appendix G.

The analyses and key findings for the semi-detached house archetype are summarised below:

- Increasing construction costs to reflect higher costs that might be experienced by a smaller developer in a higher cost location (i.e. 132% of the base price). Under this scenario:
  - low-carbon heat remains cost-effective compared to a high carbon value in 2020 but is not cost-effective against a low carbon value until 2024
  - low-carbon heat together with space heat demand of 15kWh/m^2/yr is cost-effective compared to the high carbon value in 2024
  - ultra-high efficiency standards with gas are not cost-effective compared to the high carbon value until 2025
- Removing or reducing the assumed lower cost of heating distribution within homes achieving the 15kWh/m^2/yr space heating demand level reduces the cost-effectiveness of this options. However, even assuming only a 25% reduction in heating distribution costs, the ultra-high efficiency standard with an ASHP is cost-effective against the high carbon value by 2024. Allowing only a 50% of greater reduction in the heating distribution and radiator costs that can be achieved, delays the cost-effectiveness of the ultra-high efficiency standard with an ASHP against the central carbon value until 2030.
- Based on feedback from heat pump suppliers the impact of increasing the combined heating and hot water efficiency of the ASHP options by 25% was tested. This scenario reduces the lifetime costs and running costs of homes containing heat pumps, while improving their cost-effectiveness so that, in 2020, the use of low-carbon heat via an ASHP is cost-effective against a central carbon value and building to an ultra-high efficiency standard together with an ASHP is cost-effective against a high carbon value.
- Changing long run variable gas costs to the low projections published by BEIS. Under this scenario:
  - low-carbon heat is not cost-effective compared to the central carbon value until 2026
  - low-carbon heat together with ultra-high efficiency standards is cost-effective compared to the high carbon value from 2023
- Changing long run variable gas costs to the high projections published by BEIS. This scenario increases the running cost savings and cost-effectiveness of all options so that an ASHP is cost-effective against the central carbon value in 2020 and ultra-high standards with an ASHP are cost-effective against a high carbon value in the same year and against a central carbon value in 2025
- Changing the heat supply mix for the small flat with ASHP from a 70:30 mix between heat supplied by communal ASHP and gas boilers to a scenario with 100% of heat supply coming from an ASHP (an installed capacity of 4kW per unit). This scenario increases the costs of the ASHP system, but the system remains cost effective for these homes from 2020.

6. Non-domestic buildings

Modelling results are shown for the two non-domestic archetypes including:

- Build costs
  - Impact on capital costs compared to the Part L 2013 notional specification
  - Projected capital cost impact between 2020 and 2030
  - Retrofit costs in a 2030 retrofit year
  - Comparative costs of different standards when delivered as new build or via subsequent retrofit
- Lifetime costs
  - Including impact on present value build costs, replacement and maintenance costs, energy costs (using long run variable cost of energy) in 2020
  - Annualised occupier cost (including replacement, maintenance and retail energy costs) against capital cost
- Cost-effectiveness and carbon savings
  - Trends in cost-effectiveness reflecting both changes in present value lifetime costs and in the comparative average carbon value for buildings constructed between 2020 and 2030.
  - Carbon savings against present value lifetime costs and by comparison to the CCC's average carbon value over the 60-year life of the building, weighted by discounted carbon abatement in each year.

Table 6.1 summarises the descriptions used to define each combination of efficiency (including fabric and services measures) improvement over the Part L Target Emission Rate and heating system in the subsequent results.

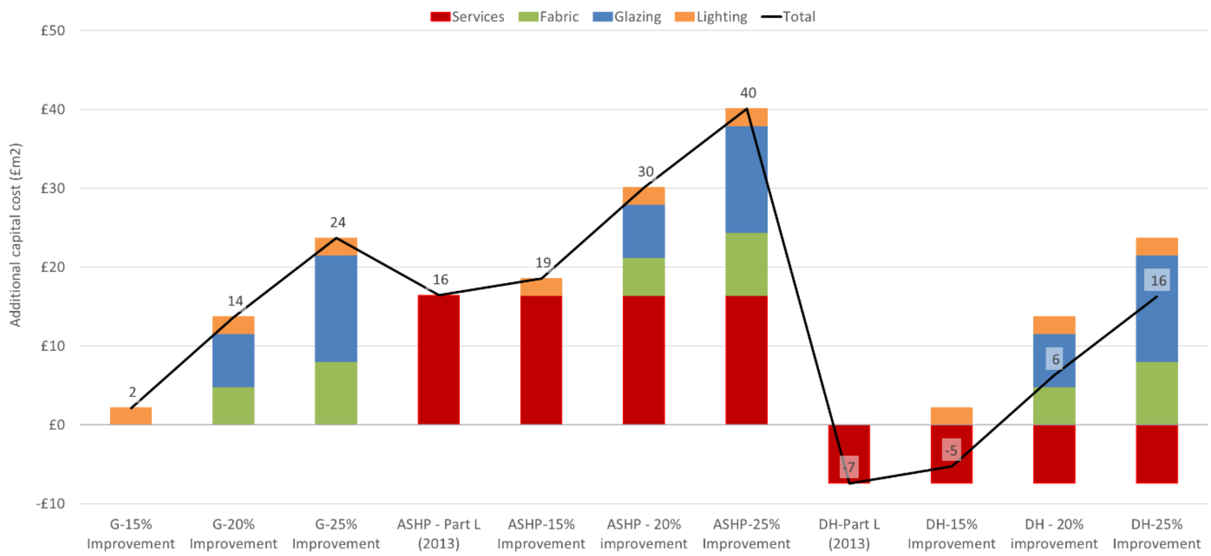
Table 6.1 Description of combined space heating energy efficiency and heating source options

Improvement in building emission rate compared to Part L minimum	Heat Source		
	Gas Boiler	ASHP	LCHN
Part L Notional	*G-Part L Notional*	*ASHP-Part L*	*DH-Part L*
15% improvement	*G-15% improvement*	*ASHP-15% improvement*	*DH-15% improvement*
20% improvement	*G-20% improvement*	*ASHP-20% improvement*	*DH-20% improvement*
25% improvement	*G-25% improvement*	*ASHP-25% improvement*	*DH-25% improvement*

6.1 New build capital costs

For the naturally-ventilated and air-conditioned offices, Figures 6.1 to 6.2 show the additional capital costs for achieving varying improvements in efficiency in combination with different heating systems in comparison to an equivalent building built to a Part L 2013 notional specification. For the LCHN options the cost uplifts exclude the costs of the network and are limited to the cost of systems within the building and a short network connection.

Figure 6.1 Additional capital costs of improved energy efficiency in combination with different heating systems – naturally-ventilated office in 2020

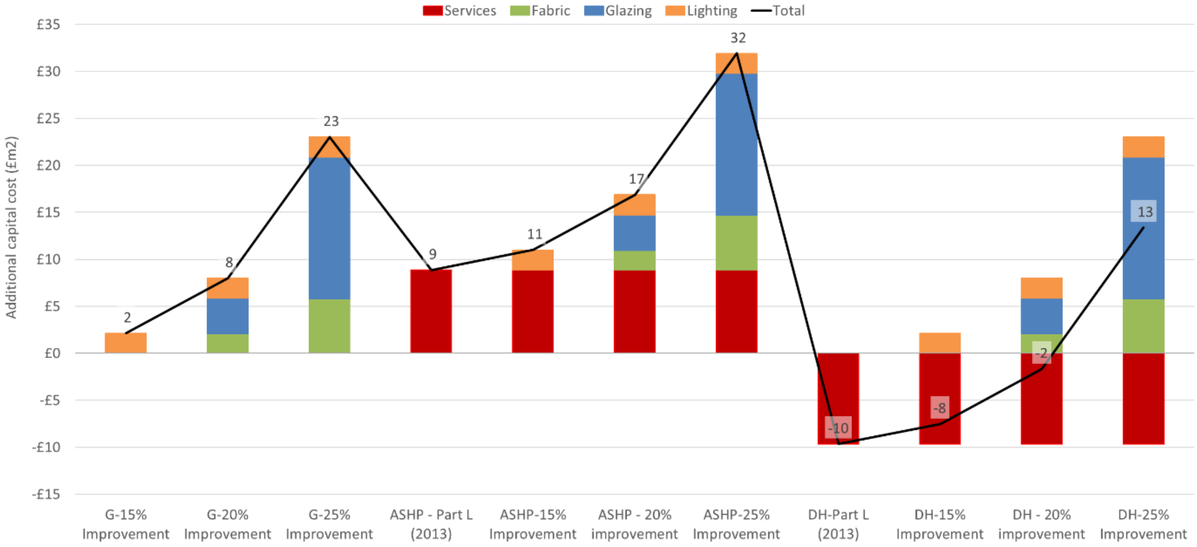


Key findings:

- A 15% improvement in naturally ventilated offices can be achieved solely using high efficiency lighting (around 95 luminaire lumens per circuit Watt).
- Further improvements require enhancements of fabric or glazing.
- Installation of an ASHP is estimated to increase construction costs by c.£16/m^2 while connection to the illustrative LCHN may result in a saving in construction costs of around £8/m^2 because of the avoided heating plant which outweighs the costs of connection and relevant heat interface units[80].
- With a typical construction cost of between £2,000 and £2,500 per m^2, the cost uplifts associated with each option are under 1% for all options except the 20% and 25% improvement options with ASHP where the uplift is still under 2% of base case capital cost.

[80] It is important to remember that the actual costs of connection will vary substantially depending on project specific circumstances.

Figure 6.2 Additional capital costs of improved energy efficiency in combination with different heating systems – air-conditioned office in 2020



Key findings:

- The results for the air-conditioned office archetype show a similar pattern to those for the assessed naturally-ventilated office, albeit some of the absolute cost uplifts vary as a result of the different size and key ratios in each archetype (i.e. the ratio of external wall / glazing / roof areas to internal floor area).
- With a typical construction cost of between £3,000 and £3,500 per m^2 the cost uplifts associated with each option are under 1% for all options.

6.2 Retrofit costs

Figures 6.3 and 6.4 show the cost of achieving energy efficiency and heating system standards as a retrofit to naturally-ventilated and air-conditioned offices originally built to the Part L 2013 notional specification with gas heating.

Figure 6.3 Capital cost of retrofitting a naturally-ventilated office to higher energy efficiency standards and an ASHP in 2030

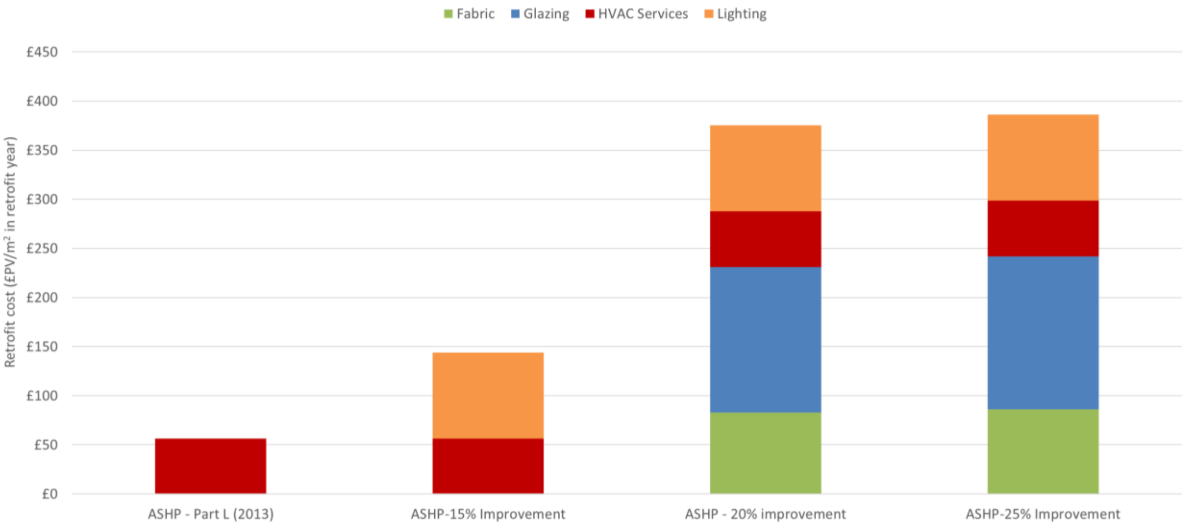
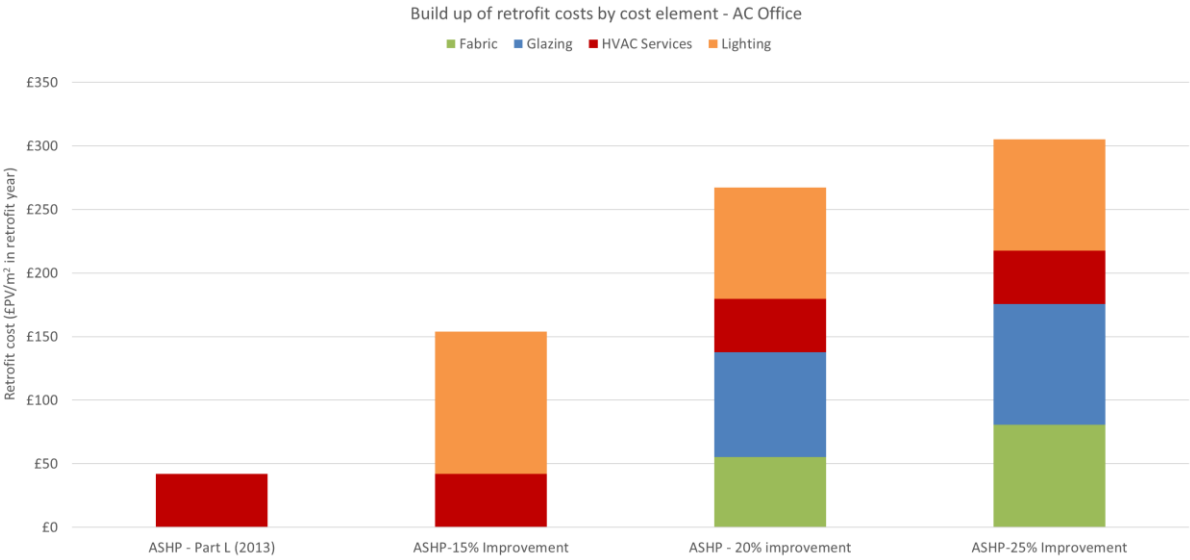


Figure 6.4 Capital cost of retrofitting an air-conditioned office to higher energy efficiency standards and an ASHP in 2030



Key findings:

- For both the naturally-ventilated and air-conditioned offices, the costs associated with achieving higher standards via retrofit are from five times to more than ten times higher than achieving the standards in a new building.

6.3 Lifetime costs

From a social perspective, lifetime costs include the capital cost, replacement and maintenance costs over a 60-year lifespan and the long run variable cost of energy. The long run variable cost of energy captures the societal costs of energy supply including generation, transmission and distribution but does not include carbon or other taxes or supplier profits.

Figures 6.5 and 6.6 shows the impact on lifetime costs estimated for each of the heating and space heat demand combinations considered for the assessed naturally-ventilated and air-conditioned offices.

Figure 6.5 Impact on lifetime costs of different heating system and energy efficiency standards in a naturally-ventilated office built in 2020

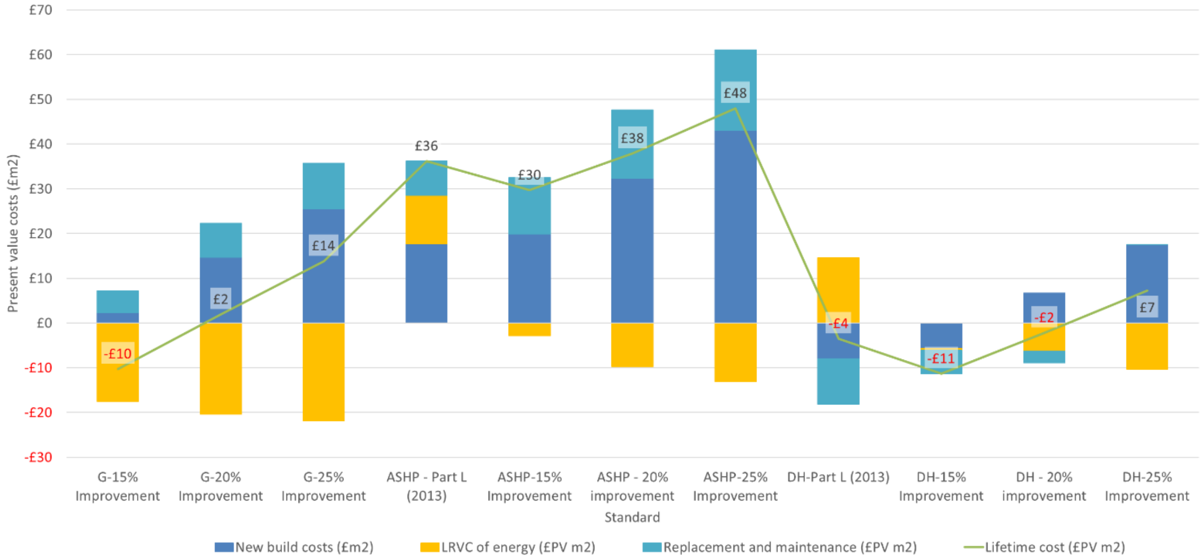
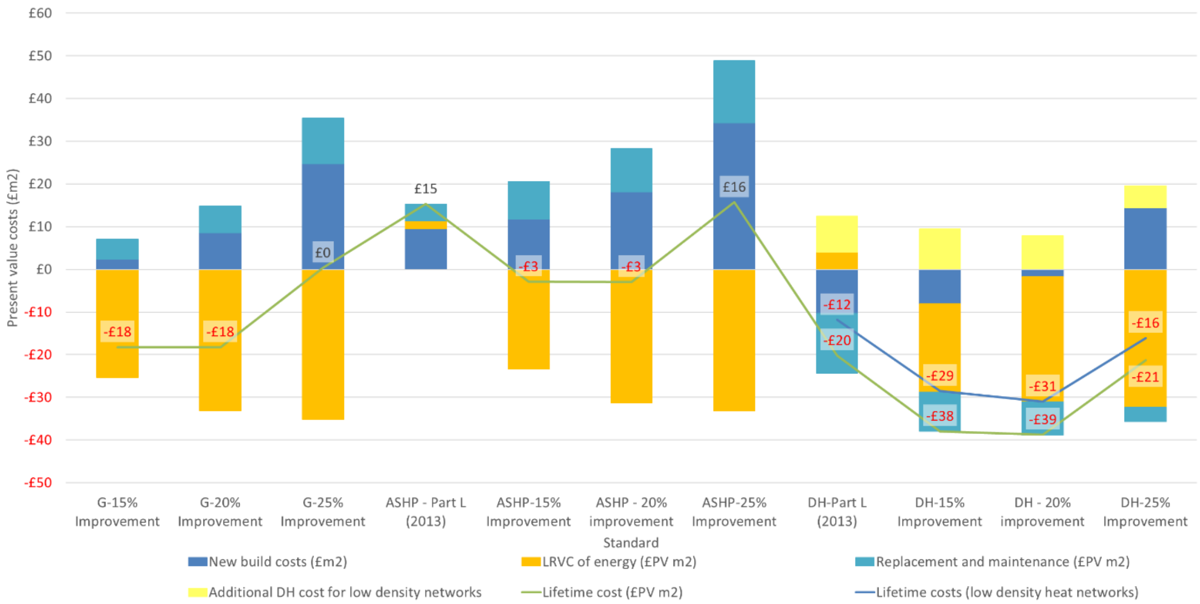


Figure 6.6 Impact on lifetime costs of different heating system and energy efficiency standards in an air-conditioned office built in 2020



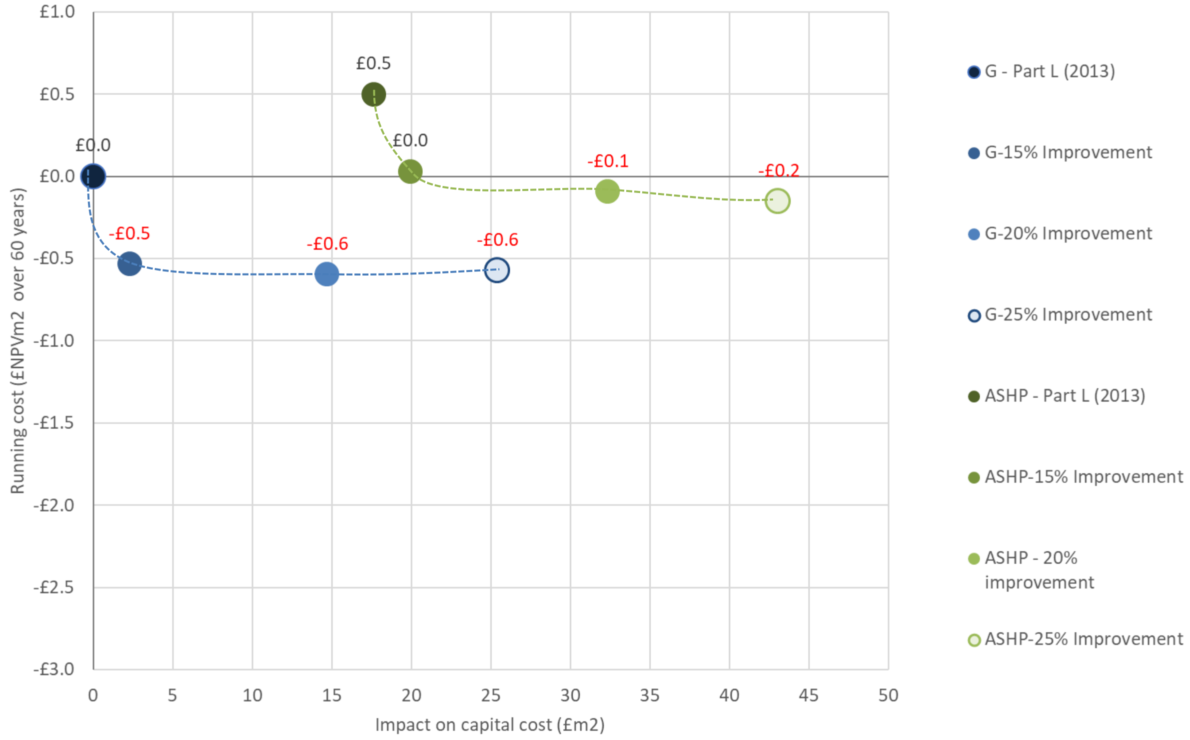
Key findings:

- For both office types, but particularly for the air-conditioned office, the lifetime cost implications of the improved energy efficiency standards are dominated by the savings in energy costs. This is largely driven by the very significant energy savings arising from the use of high efficiency (LED) lighting systems in comparison to the lighting efficiencies assumed in the SBEM method.

- The use of an ASHP alone does increase lifetime energy costs but these are more than offset by the savings from improved lighting efficiency where used as part of the improvement options.
- The energy savings from use of LED lighting are slightly offset in both offices by an increase heating demand to compensate for reduced heat output from lighting[81]. However, the additional demand is outweighed in the air-conditioned office by a larger reduction in the cooling load also as result of the lower level of lighting heat output. As a result, the overall energy cost savings from using low energy lighting are significantly greater in the air-conditioned office type.
- The scale of savings from lighting efficiencies means that for the air-conditioned office, even the higher energy efficiency levels requiring a more substantial capital cost outlay (20-25% improvement with gas and 15-20% improvement with ASHP and all of the LCHN connected options) still deliver lower or comparable lifetime costs than the base.

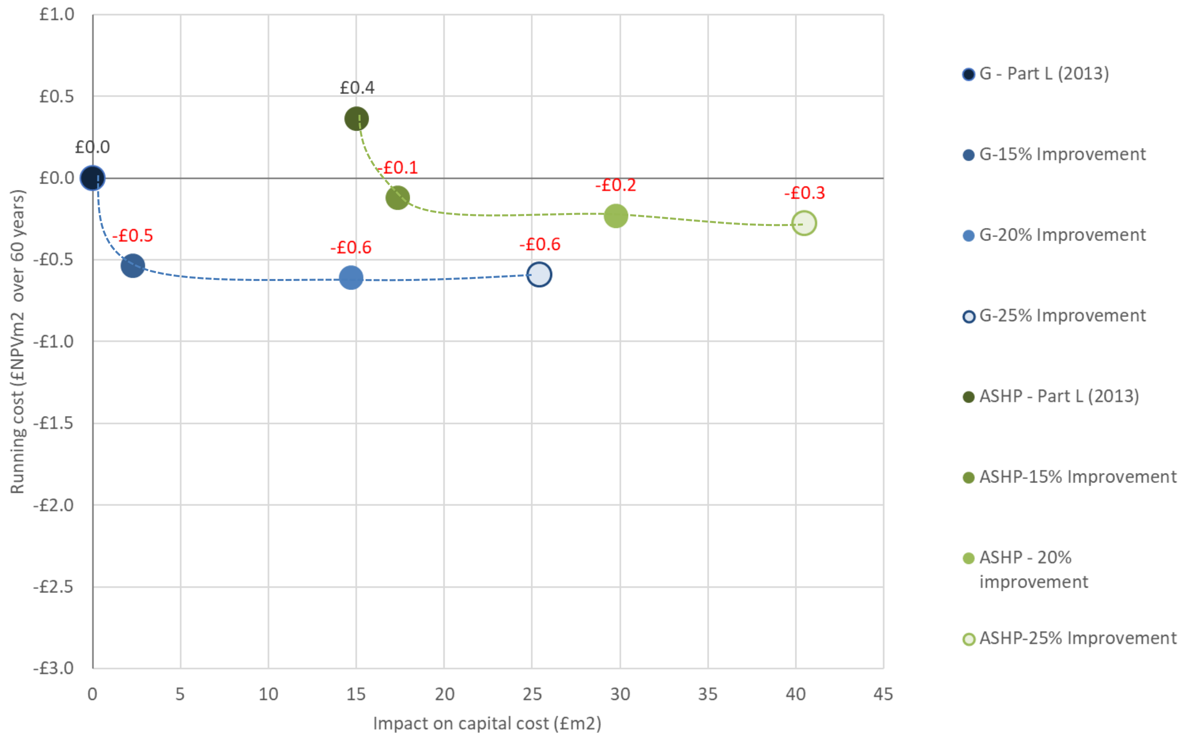
Figures 6.7 to 6.10 show the comparative running and capital costs of the various energy efficiency standards with gas heating or ASHP for the naturally-ventilated and air-conditioned offices in both 2020 and 2025.

Figure 6.7 Relative running and capital costs for a naturally-ventilated office with different heating systems and space heating demand in 2020



[81] Whether this effect would in fact arise in reality is debatable as the heat output of fluorescent lighting is low.

Figure 6.8 Relative running and capital costs for a naturally ventilated office with different heating systems and space heating demand in 2025



Key findings:

- Increasing lighting efficiency to achieve a 15% improvement on the Part L notional specification delivers the most significant reductions in running costs. Further improvements in efficiency deliver only small additional running cost savings. The small difference in saving between the 20% and 25% improvement options is because the specification to meet the 20% improvement exceeds this requirement slightly, delivering a saving of 22%. As a result, it is only a slightly smaller improvement than the specification meeting the 25% target.
- Low-carbon heat via an ASHP has a higher running cost than the equivalent specification using gas heating but when combined with efficiency measures the annualised running cost is lower than that for the notional specification with gas (G-Part L).

Figure 6.9 Relative running and capital costs for an air-conditioned office with different heating systems and space heating demand in 2020

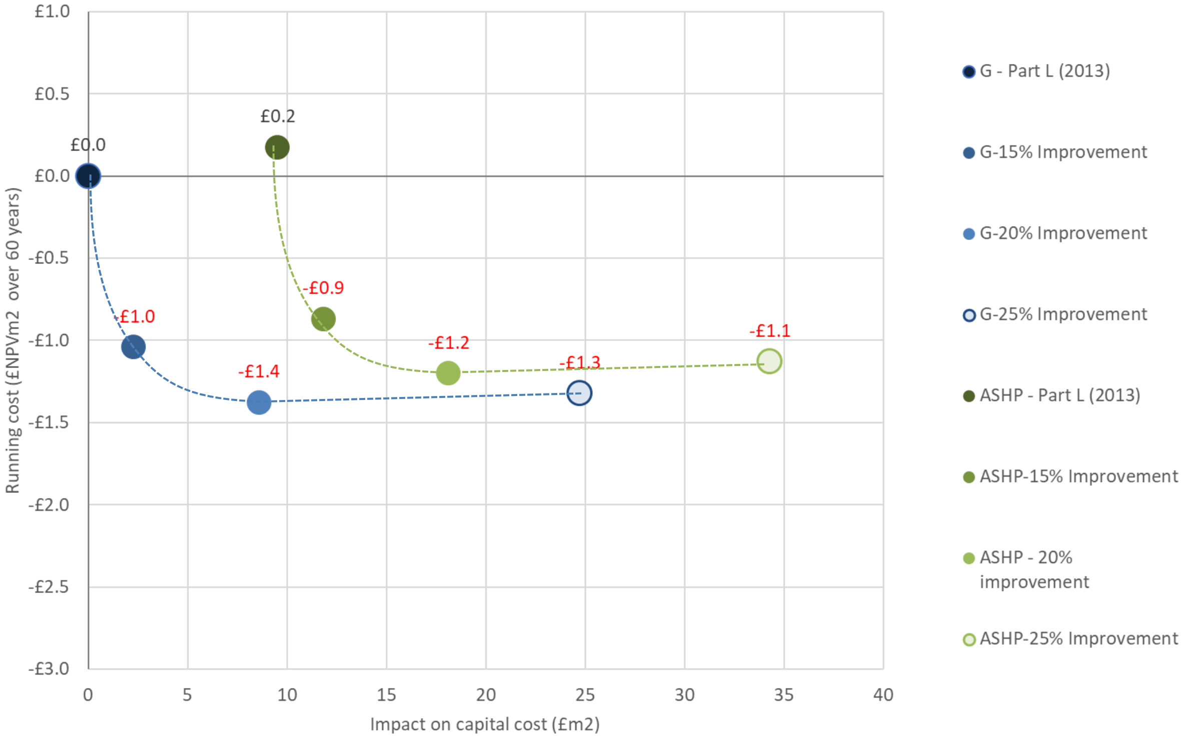
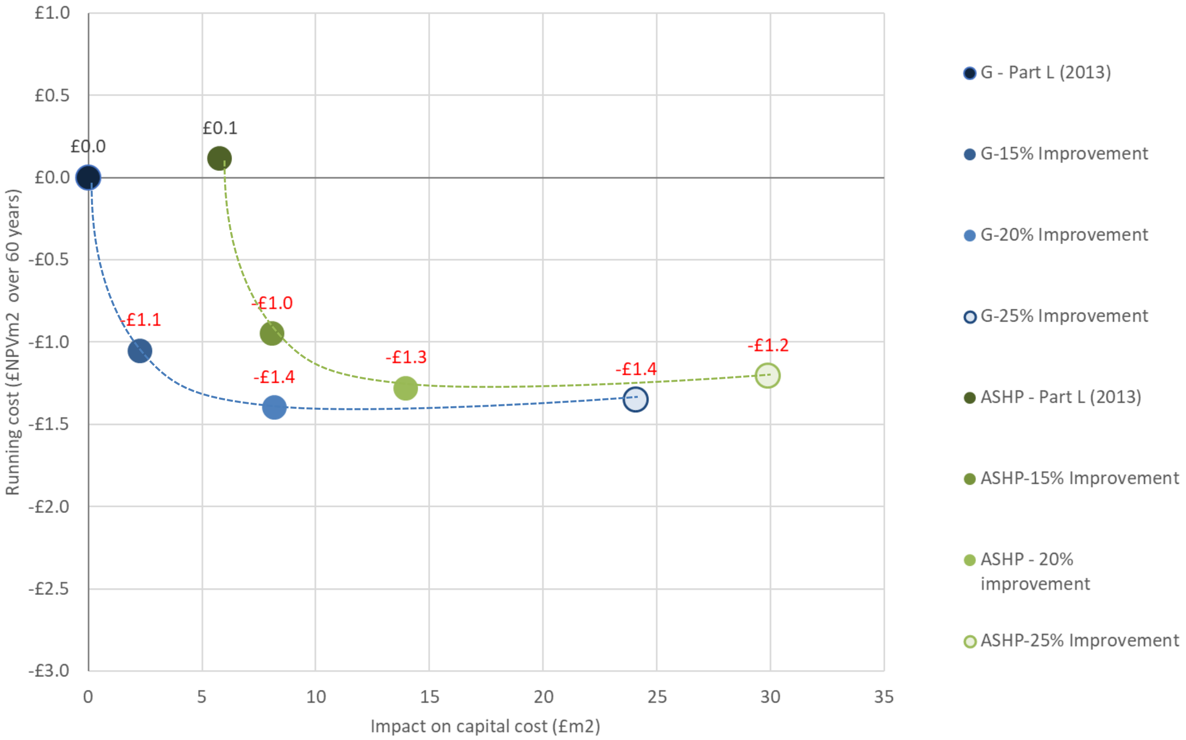


Figure 6.10 Relative running and capital costs for an air-conditioned office with different heating systems and space heating demand in 2025



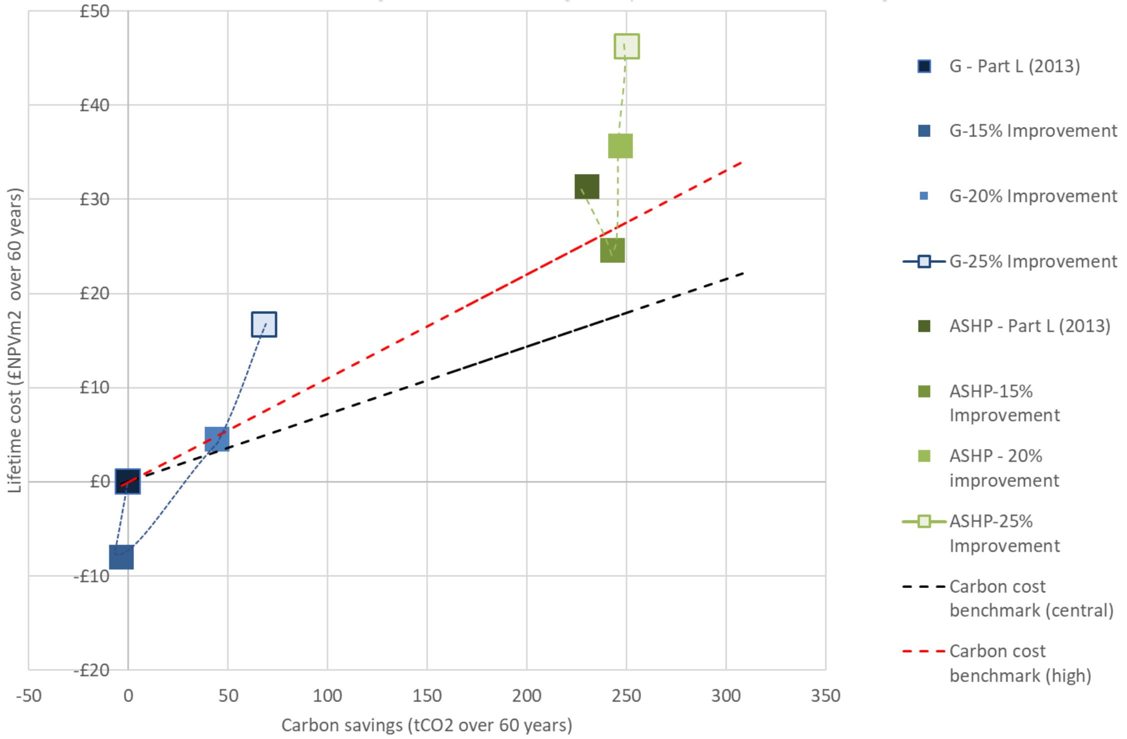
Key findings:

- The most significant savings in running costs arise from the adoption of high efficiency lighting. Further reductions in running cost can be achieved through further services efficiency (to achieve a 20% improvement against Part L) but there is little if any additional running cost saving associated with the substantially increased cost needed to achieve a 25% improvement.
- Low-carbon heat via an ASHP has slightly higher running costs than the equivalent specification heated with gas. However, an ASHP and improved efficiency delivers savings in running costs compared to the Part L notional specification.

6.4 Cost-effectiveness

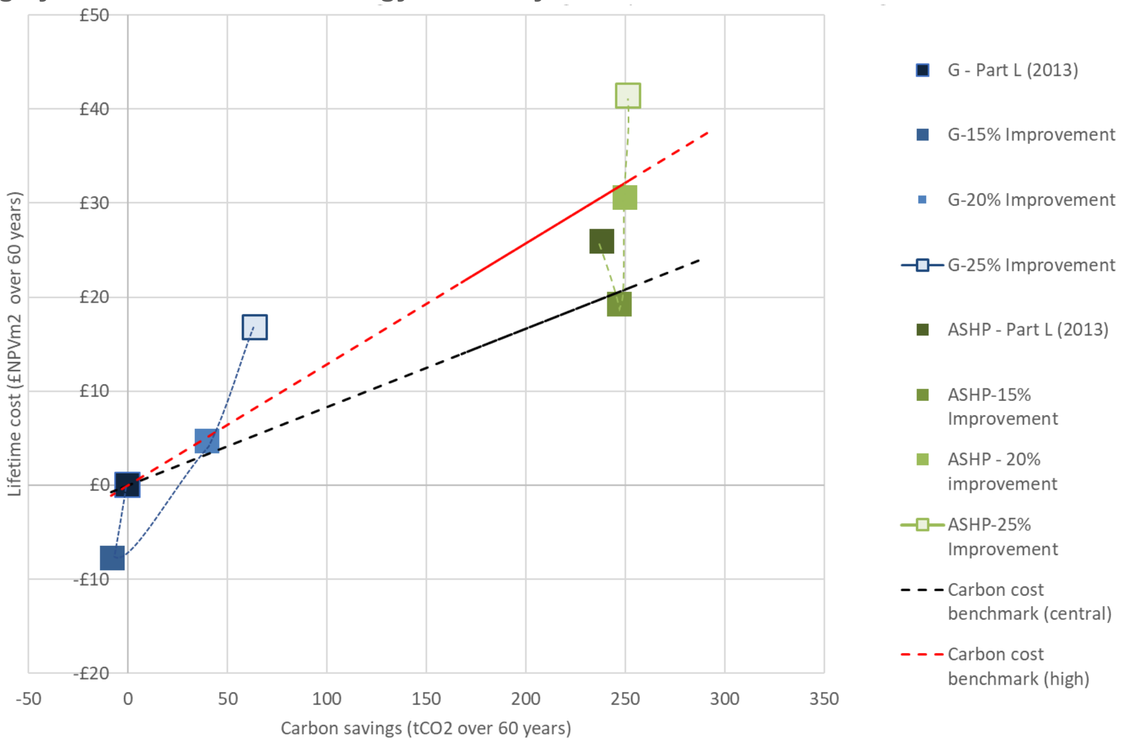
Figures 6.11 to 6.14 show the carbon savings and lifetime costs of the naturally ventilated and air-conditioned offices built in 2020 and 2025 with gas and ASHP heating and to energy efficiency standards. On each chart two lines show the price of an equivalent carbon saving based on the CCC's discounted weighted[82] price of carbon over the 60-year lifetime of the home, with the lower line representing central carbon values, and the higher line representing high carbon values.

Figure 6.11 Carbon savings and lifetime costs of naturally ventilated office with different heating systems and levels of energy efficiency in 2020



[82] I.e. carbon value is weighted according to the quantity of emission reductions that arise in each year. In these examples, emission reductions are proportionately higher in the early years of the homes life as they annual emissions for all scenarios reduce as grid decarbonisation reduces the carbon impact of electricity consumption.

Figure 6.12 Carbon savings and lifetime costs of naturally ventilated office with different heating systems and levels of energy efficiency in 2025



Key findings comprise:

- As with the domestic archetypes, the greatest carbon savings are achieved from the use of low-carbon heat in the form of an ASHP (approximately four times the savings of the highest efficiency standard assessed when combined with a gas boiler).
- ASHPs are cost-effective alongside tighter efficiency standards by 2025 at central carbon value, or 2020 at high carbon value. Cost-effectiveness improves between 2020 and 2025 as a result of both a reduction in the lifetime costs of the more efficient options and an increase in the comparative carbon value.
- The cost-effectiveness of the package of measures is improved by the savings associated with lighting
- In the absence of low-carbon heat, a 20% efficiency improvement is cost-effective in 2020 against a high carbon value.

Figure 6.13 Carbon savings and lifetime costs of air-conditioned office with different heating systems and levels of energy efficiency in 2020

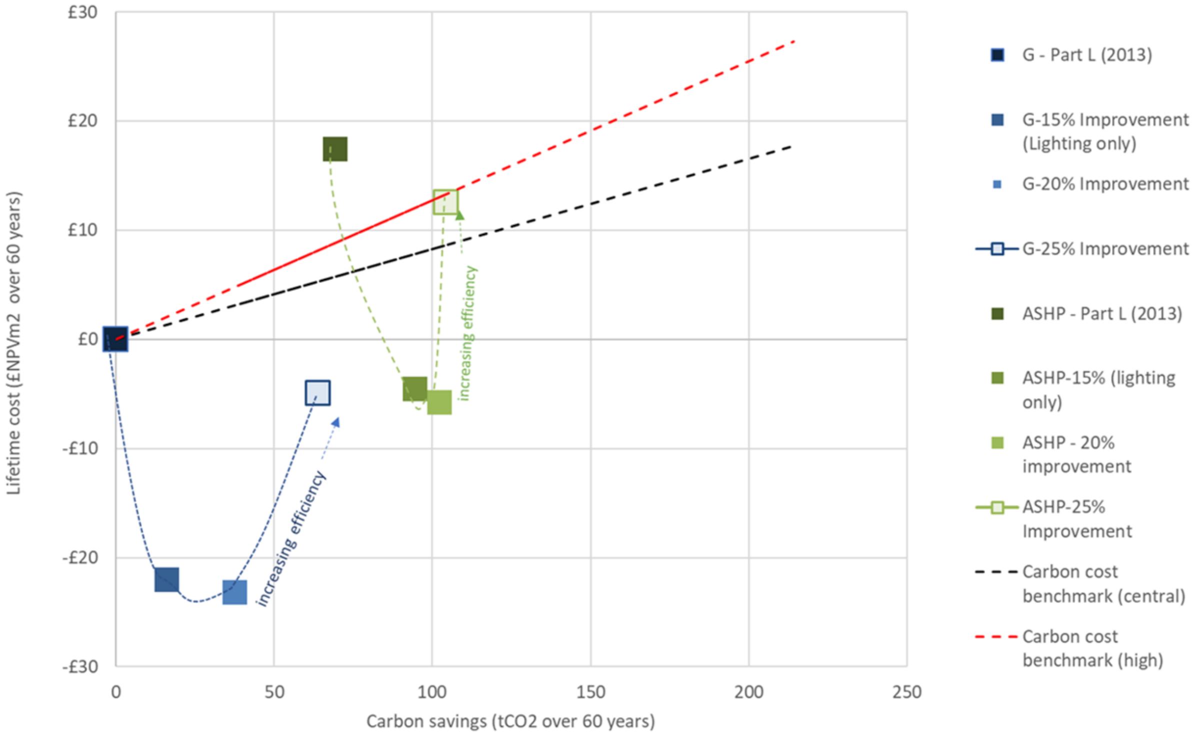
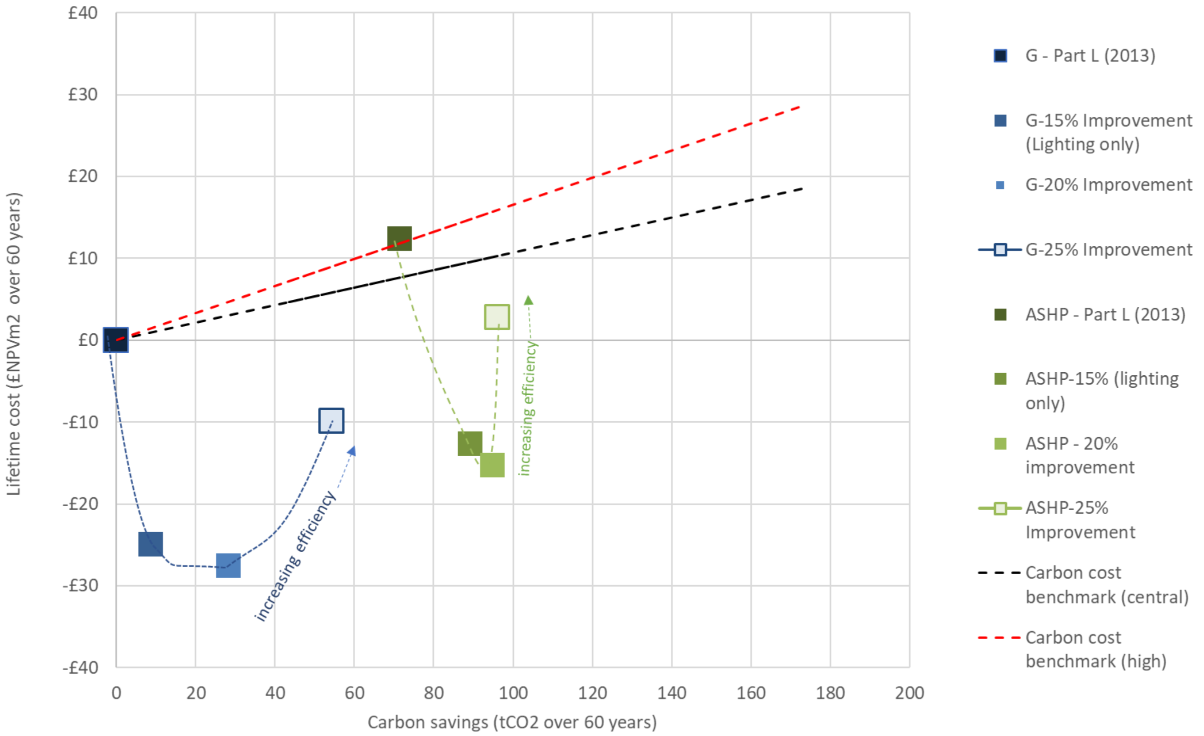


Figure 6.14 Carbon savings and lifetime costs of air-conditioned office with different heating systems and levels of energy efficiency in 2025



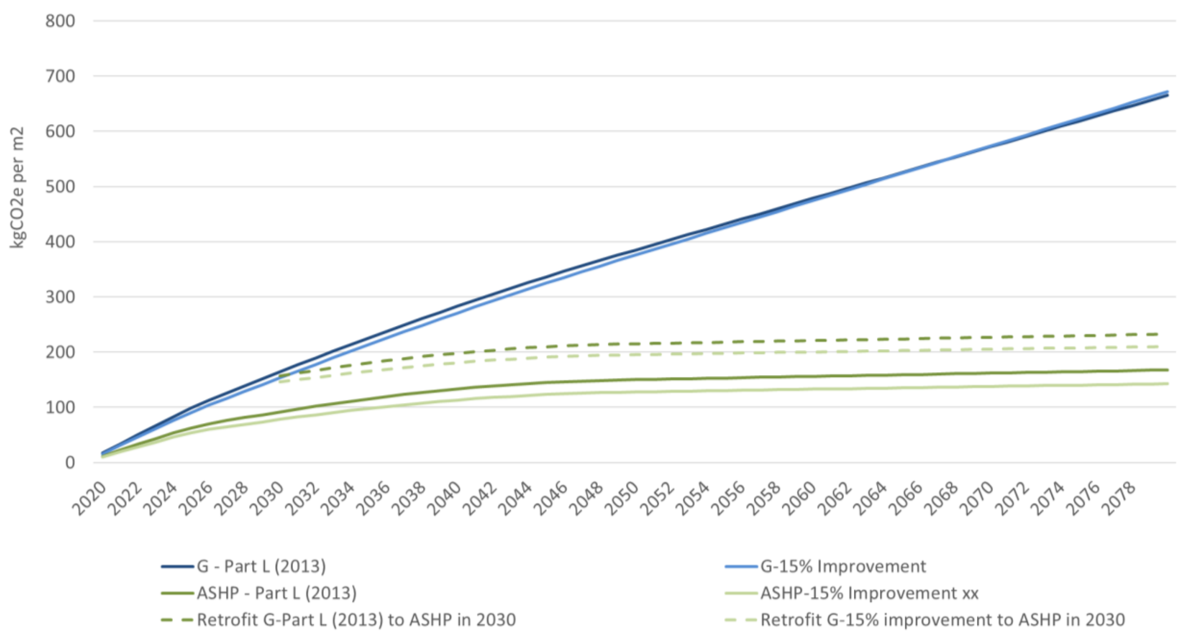
Key findings comprise:

- Patterns of cost effectiveness in the air-conditioned office are relatively different to the naturally ventilated office due to the greater energy and carbon savings associated with improved lighting efficiency and the relatively smaller contribution of low carbon heat to overall energy use and carbon emissions.
- An ASHP is cost effective alongside tighter efficiency standards (a 15-20% improvement) by 2020 at central carbon values and offers greatest potential for carbon saving. As above, lighting improves cost effectiveness, and has a beneficial impact in reducing energy used for cooling.
- In the absence of supporting efficiency measures an ASHP appears less cost-effective than in naturally ventilated offices. This is because energy use for heating is much lower in the air-conditioned building [83]and therefore the level of savings associated with the heat pump are reduced relative to the cost of the system.
- In the absence of low-carbon heat, a tightening of up to 25% in 2020 is cost-effective

6.5 Carbon savings

Figures 6.15 shows the cumulative carbon savings of a naturally ventilated office heated with gas boilers or ASHP built to either the Part L Notional or 15% more energy efficient standard in 2020. The impact of the retrofit of an ASHP into a gas heated building in 2030 on cumulative lifetime carbon emissions is also shown. Figures 6.16 provides the same analysis for the air-conditioned office.

Figure 6.15 Cumulative carbon emissions from a naturally ventilated office built to different space heating demand standards with either a gas boiler or ASHP, including retrofit of ASHP after 10 years

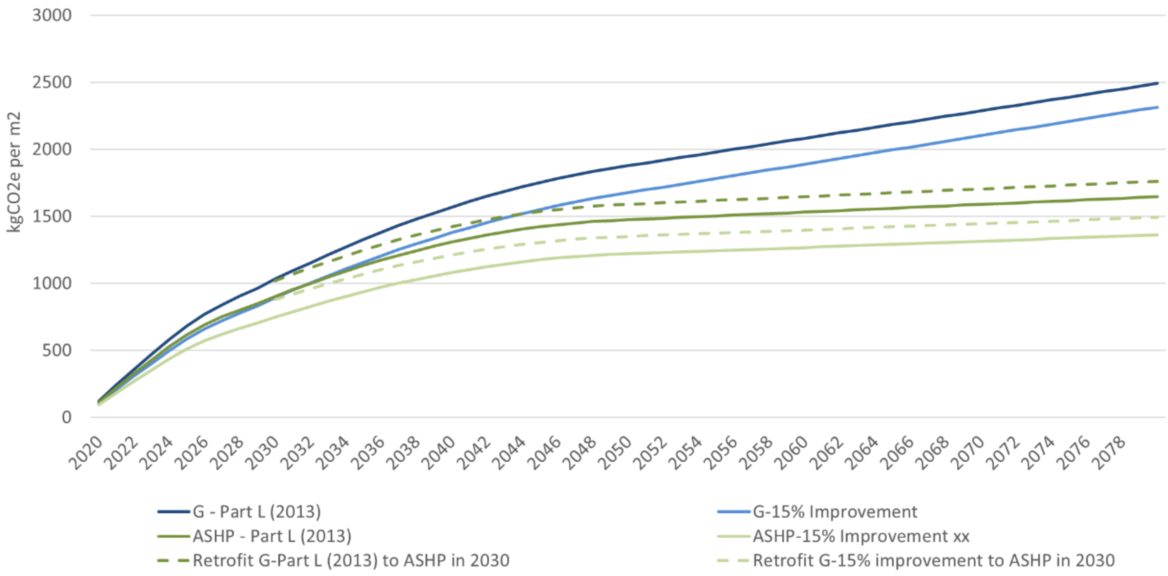


[83] There are a range of potential reasons for this including the balance of external and internal gains resulting from glazing levels, design and servicing strategy and the presence of heat recovery in the ventilation.

Key findings comprise:

- Cumulative carbon emissions over the life of the naturally ventilated office show a substantial lifetime carbon saving associated with the use of an ASHP rather than a gas boiler.
- The impact of retrofitting an ASHP in 2030 (after 10 years) is that the overall lifetime emissions are reduced substantially. However, they are still 30-40% higher than would be the case if an ASHP were installed at the point of construction.

Figure 6.16 Cumulative carbon emissions from an air-conditioned office built to different space heating demand standards with either a gas boiler or ASHP, including retrofit of ASHP after 10 years



Key findings comprise:

- The relative savings from use of an ASHP are far smaller (although still c.30%) for the air-conditioned office than for the other buildings considered in this study. This is because of the relatively small heating demand of the building, with cooling and ventilation provided by electricity in all options.
- Unlike other scenarios, the lifetime emissions of an air-conditioned office built to an improved energy efficiency standard with gas heating and then retrofitted with an ASHP after 10 years are lower than those of an office built to the Part L standard with an ASHP from the outset. This is because the carbon savings from reduced lighting and cooling energy consumption are more significant in the short term than those associated with the use of low carbon heat for the relatively small modelled heat load of the building[84]. However, given that the 15% energy efficiency saving is achieved using reasonably ubiquitous LED lighting systems it is likely that a more realistic comparison is between the 15% more efficient office with gas and the same specification with an ASHP. In this

[84] Note, some consultees feel that the modelled heat load of non-domestic offices is distorted by high levels of assumed heat output from unregulated loads within the building, i.e. the head from IT and other small power. This has the effect of reducing the modelled demand for heat.

scenario the relative carbon saving from installing a heat pump at the outset rather than as a retrofit measure is around 8%.

KEY FINDINGS

The modelling analysis described in sections 5 and 6, together with stakeholder engagement, and critical review of a variety of existing building standards and accreditation methods gives rise to a series of findings and associated recommendations for the development of future standards.

Before considering the findings arising from the modelling, it is important to review the implications of the assumptions used in current compliance models, the significance of which became apparent during the study.

7. Assumptions in building energy models used for regulatory compliance

Underpinning virtually all building standards, the national calculation method is a key variable influencing the most common solutions used for compliance. In the UK, compliance with building standards / regulations is determined using the SAP (domestic) and SBEM (non-domestic) models and accompanying assumptions. Other standards use different methods such as the Passivhaus Planning Package (PHPP) software used for demonstrating compliance with the Passivhaus and AECB building standards.

These assessment methods rely on a set of underlying assumptions and input parameters which impact on the energy demand and carbon emissions calculations/outputs, and in turn determine compliance.

The calculation method becomes increasingly significant as the level of flexibility within the standard increases. This is because the method informs decisions about the relative contribution made by, for example, measures to reduce heat loss and steps to switch to a lower carbon energy sources. Whilst flexibility in determining compliant solutions can be valuable in enabling innovation in responses, greater flexibility within a standard makes it more important that the method and metrics used to assess compliance are appropriate and well designed.

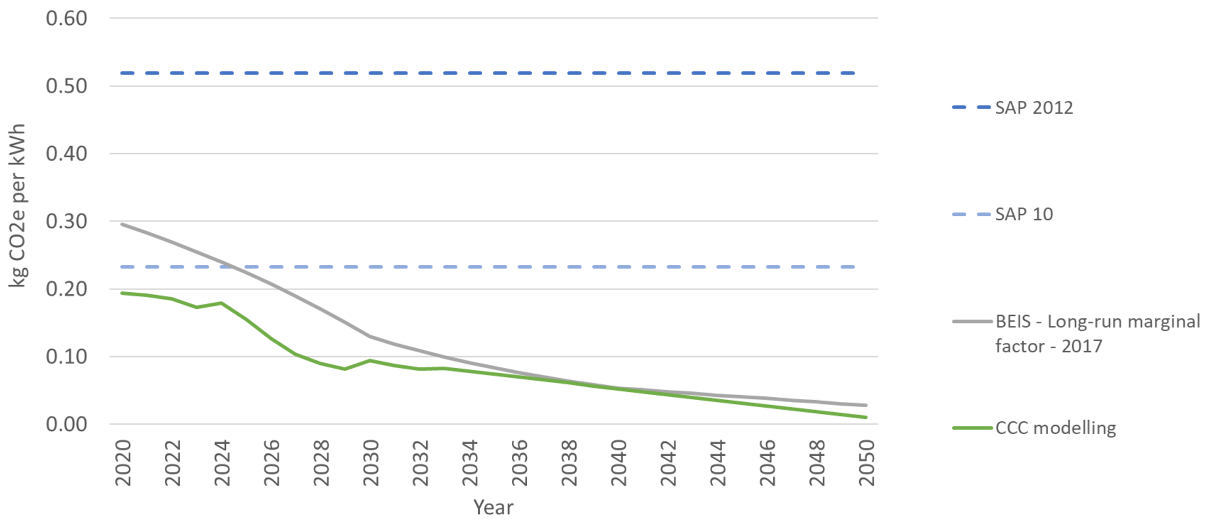
Carbon intensities and other assumptions such as system efficiencies within current compliance models do not provide effective signals to standard setters or project teams about the impact of investment made to reduce carbon emissions and may encourage the selection of solutions with higher lifetime carbon emissions.

Further, modelling tools and regulations do not adequately consider some key parameters that will be critical to ensuring new homes support the delivery of a low-carbon energy system. These considerations include peak energy demand, synchronicity of power generation and demand, and overheating risk.

7.1 Carbon intensities

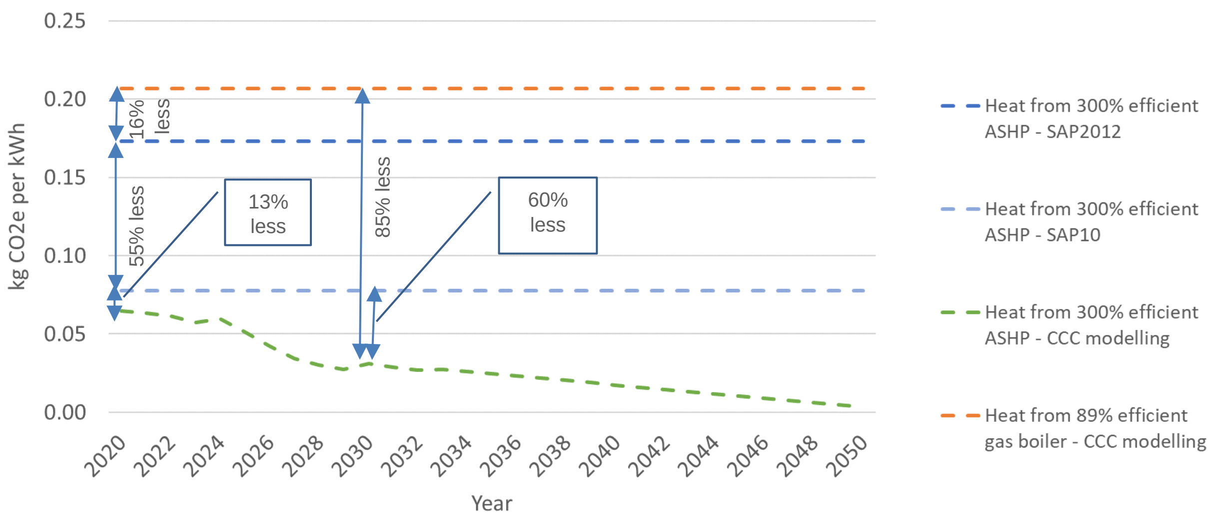
The carbon intensity of grid electricity is significantly overestimated in current regulatory compliance tools with the result that the carbon saving objectives of the regulations are not realised. While the proposed updated modelling tool for housing (e.g. SAP 10) includes more representative data on the current carbon intensity of electricity generation, it does not consider impact of projected further reductions in carbon intensity of electricity in coming decades. As a result, SAP 10 still overestimates the likely emissions associated with electricity use over a building's lifetime (see figure 7.1), thereby underestimating the effectiveness of electrical heating and heat recovery systems and overestimating the benefits of onsite electricity generation.

Figure 7.1 Assumed carbon intensity factors used in SAP and those projected by CCC and by BEIS[85]



Once the significant energy efficiency gain of a heat pump in comparison to a condensing boiler is factored into the analysis the relative carbon savings of this technology per unit of delivered heat are very substantial using projected real emission factors but are small using those factors in SAP 2012 or even the recently published SAP 10 (see figure 7.2).

Figure 7.2 Implications of using different carbon intensity factors for electricity use on the relative emissions per unit of heat output from gas or ASHP technologies



The implications of the emission factor for gas and electricity are profound. The move from SAP 2012 to SAP 10 alone signifying a reduction in the carbon intensity of electricity by over 55%. This means that the carbon emissions of an electrically heated home modelled in SAP 10 would

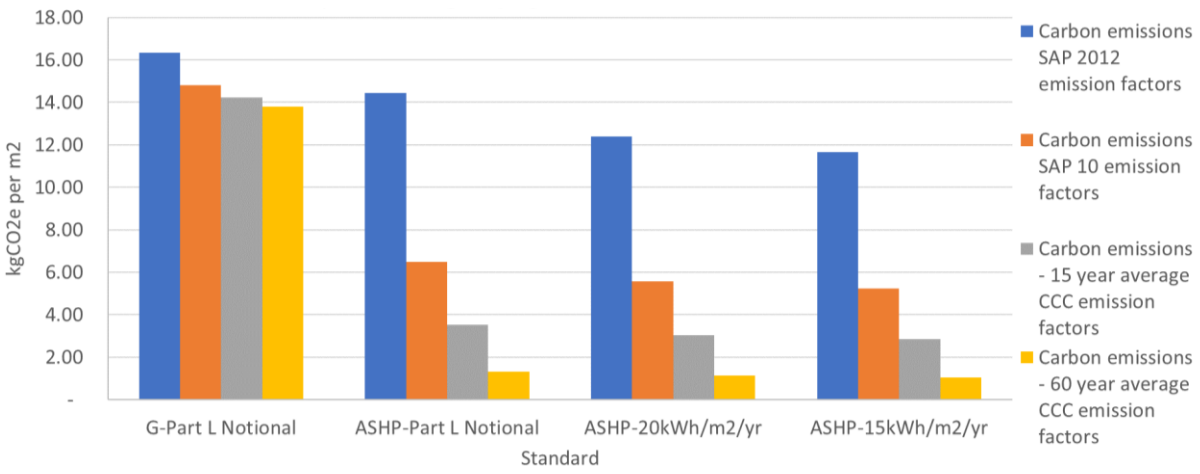
[85] BEIS, 2018. Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal - Data tables 1 to 19: supporting the toolkit and the guidance.

be less than half those of the same home modelled in SAP 2012. This trend is set to continue (see figure 7.2), with CCC projections indicating a further 60% reduction in the carbon intensity of electricity by 2030. Therefore, within the lifetime of the heating system installed in a building constructed in 2018, the emissions from electricity use could be nearly 85% lower than that modelled in the currently used compliance tool. Given that there is currently a cost premium from installing a heat pump rather than a gas boiler, the level of operational carbon saving associated with this option is highly influential in determining whether it represents a cost-effective carbon reduction choice when compared to other options.

The SBEM tools used for assessing compliance in non-domestic buildings are also subject to the distorting effects of using outdated emission factors or those based on a short-term view of the carbon intensity of different fuels.

Figure 7.3 shows the impact of these varying approaches to determining emissions factors on the relative carbon emissions per m^2 floor area of a semi-detached home built to the Part L Notional specification with either a gas boiler or an ASHP and also when built to the higher 20 kWh/m^2/year and 15 kWh/m^2/year standards and combined with an ASHP.

Figure 7.3 Carbon emissions per m^2 using different emission factors



A key challenge for compliance tools is to provide a consistent and predictable evaluation method whilst still reflecting the current and likely future real impact of energy use. The Zero Carbon Hub[86], previously proposed a rolling average emission factor covering the projected carbon intensities of different fuels over next 15 years. This approach seems suitable in that it would capture the impact of future emissions within all or most of the lifespan of the key services in the building whilst also being capable of being updated annually but with relatively little year to year change (as typically only one of 14 years would be changed in any given year).

7.2 Peak demand

The peak demand for energy required to meet a winter heating requirement can be several times the baseline level of electricity consumption. Even where an efficient heating technology such as a heat pump is used, the increase in demand on the electricity grid associated with a substantial increase in electrically powered heating could be significant. High levels of peak demand have at least two adverse consequences.

[86] Zero Carbon Hub, 2010. Carbon Compliance for Tomorrow's New Homes: A review of the modelling tool and assumptions - Topic 2 Carbon intensity of fuels.

- There is an increased need for electricity generation or storage capacity to provide the necessary power. The additional capacity will be relatively poorly utilised if peaks are large but infrequent and, if additional peak supply is via gas powered generation, could result in higher carbon emissions compared to off peak supplies.
- Supplying the necessary electricity would, in many situations, require additional investment in power transmission and distribution infrastructure in the form of higher capacity cables and / or substations. The cost and disruption associated with increasing the capacity of these systems could be very considerable in some locations.

Unfortunately, current SAP and SBEM compliance models do not currently consider the contribution of buildings to demand peaks[87] and there is no criterion within regulatory compliance requirements that explicitly or implicitly address this issue.

Peak demand can be reduced through several means including higher fabric standards, thermal or battery storage or using advanced control systems. High levels of fabric efficiency should result in less need for alternative peak reduction measures as heat can be provided to the home at a low level over an extended period and 'pre-heating' is possible due to the building's ability to retain heat. The detailed relationship between fabric standards and demand peaks would benefit from further investigation.

Consideration should be given to whether standards can play a role in reducing the impact of new buildings on peak demand. The PHPP tool used to assess compliance with Passivhaus standards does incorporate analysis of peak heating demand under two different worst-case scenarios and this method (if not the specific demand standard) could form the basis of a test to be applied within future building standards.

7.3 Photo-voltaic deployment and synchronicity of onsite power generation and demand

A related issue to peak demand is the synchronicity of energy generation and demand (including heat demand) at a building and system scale, which has important implications in the context of PV deployment.

Currently, neither SAP nor SBEM distinguish between reducing use of grid electricity and export of electricity into the grid when assessing the net carbon emissions of a building[88]. This means that reducing electricity demand by 1kWh would have the same carbon impact as generating a kWh of power from photovoltaics.

This means that the carbon benefit of energy exported to the grid, for example in the day in the middle of summer, is deemed to have equal carbon impact as energy used at night in the middle of winter. In practice, this 'netting' of the carbon emissions associated with energy use and generation, does not reflect the true system impacts as the carbon intensity and cost of supplying power at different times of day and year varies considerably[89].

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[87] Although dynamic simulations used for more complex non-domestic buildings can provide this analysis.

[88] Both compliance methods do maintain separate emission factors for electricity supplied from the grid and that exported to the grid but they are set at the same value and so there is no distinction in practice between demand reduction and electricity generation

[89] For example, electricity exported to the grid is of substantially reduced value if it is available at times when there is insufficient demand unless energy can be stored for use when demand is higher. This is because it will not result in substantial displacement of fossil fuel based generation when demand is

Where the carbon emissions associated with energy saving and generation are not equivalent, depending on their timing in the day and year, then there will be sub-optimal results if their impacts are treated interchangeably.

This 'netting' of emissions associated generation and demand becomes even more of a challenge if the carbon emissions are associated with different energy sources. For example, the carbon saving of 1kWh of electricity generation using SAP 10 emission factors is less than half that which would be expected if SAP 2012 factors were used. Further, as the electricity grid continues to decarbonise the carbon savings from electricity generated by PV reduces to almost zero. This means that, for buildings that are heavily reliant on PV to offset the impact of fossil fuel-based heating, the net carbon emissions of the building will actually increase over time.

There are a range of ways that Building Regulations could evolve to address different aspects of these issues, including at a minimum:

- Preventing onsite generation being treated as a substitute for low-carbon heating
- Ensuring that low-carbon heating technologies are properly valued in compliance methods – CCC expectations for the efficiency of technologies such as heat pumps are substantially different from those used in compliance methodologies and technologies such as solar thermal are not fully valued (for instance, SAP does not value any contribution solar thermal might make to space heating demand). These factors inhibit the uptake of low-carbon technologies.

In addition:

- Use of either time of use / seasonal emission factors to account for the timing of energy generation and consumption. As mentioned in 7.1, the projected change in these emission factors would need to be incorporated to better support decision making.
- Use of a metric similar to the Passivhaus PER method to assess the correlation between energy generation and demand
- Adoption of methods to value or account for the impacts of measures which support flexibility and peak demand management (fabric efficiency, thermal stores, batteries and controls)

7.4 Assumed levels of energy consumption and heat output from unregulated loads

A further area identified by stakeholders (but not investigated in detail in this study) is that modelled analysis undertaken using SBEM / National Calculation Methodology can significantly underestimate the heat demand of some non-domestic buildings. Analysis by Etude for Islington Council[90] identifies that compared to other, more detailed, estimation methods such as CIBSE's TM54 or PHP,P the Part L method estimates substantially lower space heating demand. More detailed methods are also more closely aligned to subsequent analysis of in use performance[91].

One reason proposed for the lower estimates of heating demand in the Part L methodology in comparison to other methods is that the Part L (SBEM) method allows for relatively high assumptions about the level of unregulated loads (e.g. IT and other small power) in the building. Heat losses from these loads are considered as contributors to the heat gain in the building thereby reducing the level of additional heating required. Where actual unregulated energy

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low and if it is not available when demand is high then alternate (and often more carbon intensive) power generation technologies are required.

[90] London Borough of Islington, 2017. Energy evidence base. Section 5.

[91] CIBSE, 2013. TM54 – Evaluating operational energy performance of buildings at design stage.

consumption is below that allowed for in the model[92] the heating system is required to make up the shortfall resulting in higher in use heating energy consumption.

An important implication of using high levels of assumed unregulated loads is that the benefits associated with measures aimed at reducing heat demand are diminished meaning that investment in improved fabric standards is not shown to have a material impact on overall energy consumption.

[92] For example, as a result of advances in IT that result in reduced heat losses from personal computers, and from reduced energy losses from, and density of, appliances such as printers, etc.

8. Potential for cost-effective carbon savings from tighter standards

This analysis identified an achievable source of very significant carbon savings associated with the use of low-carbon heating systems with further benefits associated with tightening building standard to reduce space heating demand in new homes and to improve the overall efficiency of new non-domestic buildings. The lifetime operational carbon savings from efficiency measures are typically smaller than those associated with low-carbon heat, but they are nonetheless valuable because they help to reduce running costs, overall energy consumption and levels of peak electricity demand.

1. The opportunity from low-carbon heat

- **Low-carbon heat supply is a priority** for delivering long term carbon savings. This is true of both new domestic and non-domestic buildings but is particularly important for homes and other naturally ventilated buildings. Using cost-effective low-carbon heat (via an ASHP), the regulated operational carbon emissions over 60 years of a home built in 2020 are more than 90% lower than an otherwise equivalent gas heated home. Savings of nearly 80% were identified for a naturally-ventilated office and of 30% for an air-conditioned office.
- **Photovoltaics are not a substitute for low-carbon heat.** Equivalent lifetime savings in emissions cannot be achieved using onsite renewable energy generation (e.g. via photovoltaics) to compensate for the emissions from a gas boiler. The net carbon savings associated with this generation will decline as the grid decarbonises while the emissions associated with gas use are not projected to change materially.
- **Fabric efficiency is not a substitute for low-carbon heat.** In homes, the lifetime carbon savings achievable from the use of low-carbon heat are substantially greater than even the most energy efficient fabric standards when paired with a gas boiler.[93] This is in part because the of ongoing use of gas to supply domestic hot water, which would become the most significant contributor the building's carbon emissions as the space heating demand is reduced and the carbon associated with electricity declines.
- **Low-carbon heat is cost-effective when built into new homes from 2021**. Low-carbon heating in the form of an ASHP[94] is cost-effective in all new homes built from 2021, when compared against central carbon values. In housing, lifetime carbon savings of over 90% are achieved at a capital cost uplift of around 1-2%. Connecting to a LCHN may also be a cost-effective carbon reduction solution in situations where the heat density and scale enable efficient operations[95].
- **Low-carbon heat need not increase running costs**. If buildings perform as designed, and using CCC system efficiencies, low-carbon heat via an ASHP should reduce the running costs of a home built to the Part L notional specification in comparison to an

[93] The most energy efficient home specification was that with an annual space heating demand of under 15kWh m^2.
[94] An ASHP has been used to illustrate onsite low-carbon heating sources. Other possible technologies include ground source heat pumps (GSHP) or even the use of solar technologies together with thermal or battery storage. Hydrogen has not been modelled here as a low-carbon heating option because it is assumed to would require conversion of the gas grid rather than being applicable to new homes as a bespoke solution. Hydrogen has been considered separately in CCC advice (see for example CCC (2018) *Hydrogen in a low-carbon economy*).
[95] The costs and cost-effectiveness of LCHN connections will vary considerably according to the development type and context. Results of the single LCHN scenario considered in this report, should therefore be taken as indicative only. This study prioritises consideration of ASHP as a more widely applicable low-carbon heat source.

equivalent home with a gas boiler[96]. However, running costs of an ASHP could be higher if the system is poorly designed, installed or commissioned, or if the occupier does not use the system correctly. In ultra-high efficiency buildings, the risk of increased running costs is substantially reduced, with potential for annualised savings of around £85-100 per year for a semi-detached house.

- **The carbon penalty for delayed action is significant**. As figure 5.14 shows, a semi-detached home built in 2020 with gas heating and retrofitted with an ASHP in 2030 will emit more than three times more (or 9-10 tonnes) carbon over 60 years than if the heat pump was installed when the house was built. If 300,000 homes are built annually by the mid-2020s, each year of delay in adopting lower carbon heat technologies could result in several million tonnes of avoidable carbon emissions, even if the technology were to be retrofitted after only 10 years.

2. Alongside low-carbon heat, ultra-high fabric efficiency standards offer opportunities for cost-effective savings across most house types by 2025[97]

- **Tighter fabric standards deliver a range of benefits**. While low-carbon heat delivers very substantial benefits, even at current efficiency levels, there are several material benefits from tightening fabric standards alongside the installation of low-carbon heat:
  - Further savings in running costs can be achieved (around £30-£40 relative to installing a heat pump alone)[98] while also improving the quality of the internal environment
  - Reduced energy consumption reduces the quantity of low-carbon energy required to meet UK demand
  - Lower heat losses help to reduce or avoid peaks in energy demand associated with space heating[99]
  - Potential for fewer radiators and reduced heating distribution system, freeing up internal wall space, saving associated capital and maintenance costs while also reducing the risk of water damage over the building's life[100].
- **Ultra-high energy efficiency standards, installed alongside an air source heat pump, represent a 1-4% uplift on build costs relative to a home built to current regulations.** Costs are highest for the least efficient building forms such as detached houses.
- **Ultra-high efficiency housing is more cost-effective than that making smaller improvements on current regulatory requirements**. Ultra-high levels of energy

[96] Unit energy costs are slightly higher until 2040, but the avoided gas standing charge results in an overall annual cost saving.
[97] In this context ultra-high efficiency is a space heating demand of 15kWh/m^2/yr or less as modelled by SAP 2012. This is similar a Passivhaus level of performance, notwithstanding the variations in the approach to modelling performance in the Passivhaus Planning Package and SAP.
[98] The scale and nature of the bill impact is in part a function of the standing charges associated with gas and electricity bills and will vary with the scale of standing charges assumed. Where moving to and from a tariff which does not include standing charges (i.e. where these costs are incorporated in the unit rate), the saving associated with ultra-high energy efficiency standards and a heat pump relative to installing a heat pump alone could be up to £40.
[99] This is an area that would benefit from further research and consideration in standard setting. Currently SAP and SBEM energy models do not consider the scale and dynamics of peaks in energy demand, preventing the associated external costs on the energy system being fully captured.
[100] Examples of recent Passivhaus or similar ultra-efficient homes suggest that radiator numbers can be reduced from c.10-12 to 3-4 centrally located panels in a semi-detached house. Although not tested in this study, it may be possible that for ultra-energy efficient homes it is possible to avoid wet heating systems altogether and rely only on direct electric heating via ventilation and a limited number of panel heaters.

efficiency are generally found to be more cost-effective than tightening to 20-30 kWh/m^2/yr of space heat demand, due to a significant (up to c. £3,300) saving in the capital cost of the radiators and heating distribution system which helps offset some of the additional costs associated with the most energy efficient fabric specifications.

- **Where MVHR is used it should be paired with efforts to achieve very high levels of airtightness**. The use of MVHR in homes without high levels of airtightness (i.e. 2.0 m^2/m^3/hr or below) could result in additional running costs because the costs of operating the fans outweigh the savings in reduced energy consumption.
- **Tighter energy performance should be accompanied by other related standards.** Stakeholder engagement highlighted the importance of ensuring that, alongside any transition to ultra-high efficiency standards, standards and policy frameworks effectively manage overheating risks, ensure adequate ventilation and support easy maintenance of key building systems.
- **A phased transition to tighter housing standards.** An ultra-high efficiency specification for homes requires high levels of airtightness together with high performance windows and mechanical ventilation. These systems will require changes to established practices and the learning of new skills and areas of focus, especially if these changes are paired with a change to a low-carbon heating system. A phased, but concise, transition process would therefore be appropriate to enable the industry to prepare, innovate and test accordingly. Throughout the transition phase there should be support or even incentives for those wishing to move ahead of the regulatory trajectory, perhaps linked to developments securing public funding or other support.
- **Active support for transition is important**. The transition should be supported by suitable investment in support for the industry to provide tools, guidance, training and quality assurance processes that are commensurate with the challenge and scale of the opportunity.

3. There is potential to cost-effectively tighten standards for new non-domestic buildings

- **Non-domestic buildings are diverse with widely varying levels of energy demand.** Due to scope limitations the analysis in this study considers only two archetypes: a naturally ventilated and an air-conditioned office. The results are therefore indicative only, and further work is needed to assess the opportunities and costs for other building types and designs.
- **The greatest carbon savings are from low-carbon heat, but energy efficiency reduces running costs**. For the assessed offices the greatest potential carbon savings arise from the use of low-carbon heat, while energy savings, primarily through lighting and building services efficiencies, can deliver significant savings in running costs alongside this.
- **Low-carbon heat is cost-effective by 2025 or earlier when installed alongside energy efficiency measures.** Analysis suggests that low-carbon heat via ASHPs will be cost-effective in comparison to a high carbon value by around 2025. When combined with simple energy efficiency measures, such as high efficiency lighting, low-carbon heat is cost-effective in 2020 against a high carbon value and by 2025 against a central carbon value.

4. Achieving higher standards via retrofit is very expensive compared to designing them into new buildings from the outset

- **Costs of achieving higher standards via retrofit are three to five times higher than for new buildings**. The costs of installing low-carbon heat as a retrofit to an existing gas heated semi-detached home is around £9,000, over three times the cost than if the technology were installed in a new build. To improve fabric standards and install low-carbon heat via retrofit costs range from over £16,000 to more than £25,000 per home - up to five times the costs of achieving the same standards in when first constructing the home (see figure 5.8). For non-domestic buildings, achieving higher standards via retrofit is between approximately 3 and 10 times the costs of delivering them in the new building

- **Targeted preparatory measures in new buildings can significantly reduce retrofit costs**. The installation of radiators and hot water stores (where used) that are compatible with low temperature heating can reduce the costs of retrofitting an ASHP by £1,500-£5,500, depending on house type, at a capital cost of £150-£500 per home. Low temperature radiators will also provide a small improvement in the efficiency of a gas boiler prior to the retrofit of the ASHP.

5. Managing the performance gap is an important first step

- **'As built' performance is more important for low-carbon heat.** The introduction of low carbon / low temperature heating systems increases the importance of systems performing as intended to deliver the affordable comfort. This is because if a building's heat losses are substantially higher than estimated there will be a risk of the heating system being run at higher operating temperatures to meet the additional demand. This would result in substantial increases in energy use, to replace the additional heat losses and because the system is less efficient at higher temperatures. With traditional (gas) heating the reduced efficiency associated with higher than expected heat losses is far smaller.
- **Understanding the performance gap to help close or manage it**. Where investigated, a gap between design and as built performance has been identified for both housing[101] and non-domestic buildings.[102] Further work to gather information on the real in use performance of new buildings will help to better understand the scale and nature of the performance gap and assist in identifying the steps to close it so that users can have more confidence in the performance of new buildings.

6. Compliance tools and methods must change

- **Current compliance tools (SAP and SBEM) provide a poor method for estimating operational carbon emissions.** Use of static emissions factors and failure to update them for over five years means that among other things, currently used tools significantly overestimate the carbon savings from use of Combined Heat and Power (CHP) or photovoltaic (PV) panels and underestimate the savings from use of heat pumps or mechanical heat recovery systems.
- **Key assumptions need to be revised to accurately value the benefits of low-carbon technologies.** The new SAP10 compliance method includes a significant number of methodological changes, including updating the significantly out of date carbon emission factor for electricity used within SAP 2012 and incorporating new approaches to estimating hot water use and lighting energy. However, the new standard still maintains a focus on presenting the current (at time of publication) emission factor for each fuel and does not incorporate the government's projections for long-term reductions in carbon intensity of electricity. As a result, even the revised method will still substantially overestimate the expected lifetime carbon emissions from electricity use. CCC

[101] Zero Carbon Hub, 2014.Closing the gap between design & as-built performance: End of term report
[102] InnovateUK, 2016. Building Performance Evaluation programme: Findings from Non-domestic buildings.

expectations for the efficiency of heat pumps are also substantially different from those used within compliance methodologies and it is recommended that the evidence for updating assumed efficiency levels is reviewed. Finally, SAP can have a material influence on technology uptake through the technologies it includes and excludes from the methodology – currently whilst technologies such as solar PV are incorporated, technologies such as solar thermal are not yet fully valued (for instance, SAP does not allow for solar thermal to contribute to space heating needs). Recent investment in the methodologies underpinning standards has been very limited, when viewed as a proportion of the value of the economic output they influence.[103] Investment in these methodologies should be proportionate with their impact.

- **Compliance tools and requirements should consider a wider range of factors.** Current compliance tools do not adequately consider some key factors that will be critical to ensuring new homes support the delivery of a low-carbon energy system for all of the UK. These considerations include estimating the peak demand for energy associated with new homes, accounting for the synchronicity of energy generation and demand. There are precedents within international building standards such as Passivhaus for methods that could be used to address these factors.
- **There is a case for adopting absolute performance targets**. Especially for peak demand. Such an approach would reward the use of energy efficient designs, ensuring that the least efficient building forms must work harder to minimise their energy use, reducing the associated impacts on running costs and potential for higher peak demand.

7. Areas for further investigation

- The potential of hot water efficiency measures and other solutions to provide cost-effective carbon and energy savings should be investigated as part of the development of future standards. This future analysis should use modelling tools that address the considerations described previously, i.e. to ensure they appropriately value the carbon emissions from use of different fuels, incorporate the most current knowledge on system efficiencies and usage, and consider the effects of building design and specification on levels of peak as well as total demand.

[103] For instance, BEIS's 2017 'Invitation to Tender for technical services to maintain methodologies for calculating energy performance of buildings' invited tenders for development of SAP within a budget of up to £675,000 per annum (excluding VAT). This compares to an annual economic output of housebuilding of £38bn in England and Wales in 2017 according to the House Builders Federation. See House Builders Federation and Lichfields (2018) The economic footprint of House Building in England and Wales.

9. Actions and route map

Below we set out a potential route map for tightening new build standards, based on the research undertaken as part of this study. Given the parallel expectations for a substantial increase in housing delivery over the first part of the 2020s, a phased approach can help ensure that the industry has enough time to prepare for changes, and learn the associated lessons, before pursuing further changes.

The first step should be the establishment of the necessary tools to support standard development and project decisions, future standards should drive a transition to low-carbon heat together with a phased and cost-effective tightening of energy efficiency reduce running costs and minimise the demands placed on electricity generation and supply infrastructure.

1 – A robust platform and ongoing active support programme – 2019 onwards

The scale of the changes required to deliver both low-carbon heat and tighter performance standards should not be underestimated, and it is essential that sufficient investment is available to provide necessary tools and support industry change.

Government and industry should work together to provide a robust basis for delivering a transition to low-carbon heat and progressively higher levels of efficiency in new buildings. Key steps would include:

- Agreeing a route map and action plan to drive change and support the industry in delivering high quality, low carbon, affordable homes. Key themes might include: assurance of as-built performance, airtightness and ventilation, delivering low-carbon heat, training and skills (both construction and maintenance) and engaging the customer. The route map should include a jointly agreed timetable and targets.
- Initiate and maintain a process for gathering data on as built performance and on the scale and causes of any gap from design predictions. These learnings should be fed back into compliance tools, guidance and assurance processes.
- Review compliance tools so that they best support the delivery of low carbon and ultra-efficient buildings. Priorities linked to operational energy and carbon[104] are:
    - Use of a predefined update cycle that ensures the method incorporates best available data and knowledge. This may require limited processes to enable projects to ‘lock-in’ to specific compliance tool versions should they wish to avoid disruption
    - Adoption of carbon intensity factors for energy use and exported electricity that better reflect current and projected future values covering at least 10-15 years.
    - Review of efficiency benchmarks for services, lighting and unregulated loads (particularly in non-domestic buildings) to reflect evidence on actual performance and energy use
    - Explicit consideration of levels of peak demand to enable new buildings to minimise their contribution to
    - Incorporation of learnings from as built performance reviews to improve the robustness of design predictions and to incentivise the use of relevant product / design / construction standards that have been shown to minimise performance gaps

[104] The CCC have commissioned other studies considering climate adaptation needs and the carbon impacts of construction and building materials that may also need to feed into compliance tools.

- Pathfinder projects, possibly linked to Government funding schemes and the Buildings Mission[105] under the Clean Growth Grand Challenge to help further establish evidence and best practice to support the effective delivery of higher standards for energy efficiency and other future looking requirements such as assessment of whole life carbon performance
- A support body/programme to actively drive change, support the industry, promote innovation, reduce cost and manage risk. This might be similar in form to the former Zero Carbon Hub with representation across government and industry and might be delivered under the auspices of the Clean Growth Grand Challenge and wider Construction Sector Deal.

2 – Transition to low-carbon heat – 2020-25

Low-carbon heat supply is a priority for delivering long term carbon savings. This study shows that low-carbon heat is cost-effective when built into new homes from 2021 and by 2025 for the limited selection of non-domestic archetypes examined.[106] New homes using low-carbon heat could have lifetime operational carbon emissions that are more than 90% lower than an equivalent gas-heated home. A phased move to low carbon heating is required to manages transition risks and build on the industry support described in Point 1 above, with the aim of all new homes built from 2025 using these technologies. Key steps would include:

- Setting a tighter carbon target that incentivises the use of low carbon heating from 2020. Homes not using low carbon heating technologies would need to achieve significant improvements in efficiency relative to current standards and incorporate design features that reduce the cost of subsequently adopting low carbon heat
- Setting regulations in 2020 which require that all homes built from 2025 utilise low-carbon heating.
- Delivering low-carbon heating in all new homes from 2025 would also require amendments to wider regulations, which currently permit homes to be built to the standards in place at the time planning permission is granted (sometimes many years before the homes are built).

3 - Move to much tighter energy standards for new homes - by the mid-2020s

Tighter energy standards for housing will help to reduce running costs alongside minimising the contribution of new homes to annual and peak demand. Much tighter standards equivalent to space heating demand of 15kWh m^2 (when modelled in SAP 2012), together with low-carbon heat becomes cost-effective for most house types by 2025 and for all by 2027. Homes built to these standards could reduce annualised household bills by £85-£100.

To manage the transition to tighter energy standards in parallel to a move to low-carbon heat, a phased approach is recommended with tighter standards coming into force in in 2020, 2023 and 2025-7. In advance of standards tightening in 2023 and 2025-7, new developments (including

[105] https://www.gov.uk/government/publications/industrial-strategy-the-grand-challenges/missions#buildings
[106] For the non-domestic archetypes, low-carbon heating is found to be cost-effective in 2025 against the central carbon value only when combined with more efficient lighting. Without improved lighting efficiency the low-carbon heated offices are cost-effective against a high carbon value in 2025. The selected archetypes should be taken as indicative only - further work would be required to assess other non-domestic building types.

but not limited to Pathfinder projects) should be encouraged[107] to go beyond the minimum regulatory requirement and thereby ease the transition to the next level of performance.

Specific performance standards in each year will need to reflect the prevalent compliance method at the time[108] but in addition to incentivising low-carbon heat should focus on ensuring that overall energy use and running costs are minimised and that peaks in demand are avoided / managed effectively.

4 – Tighten energy and carbon standards for new non-domestic buildings 2020-2027

This study shows that there may be opportunity for reductions in the modelled carbon emissions (Building Emission Rate) of 15-25% through energy efficiency based on the non-domestic buildings assessed. Together with low-carbon heat, these measures are cost-effective against a central carbon value in 2025. These changes would deliver lifetime operational carbon savings from 30% to over 80% whilst also reducing running costs. This study only considers two office archetypes and further work would be required to determine standards for a wider range of building types. Nonetheless, there is reason to believe wider opportunities for cost-effective tightening exist in the non-domestic sector.

[107] Consideration could be given to financial incentives for developments going beyond minimum requirements, this approach has been successful in Brussels in supporting their move to Passivhaus standards.
[108] Analysis in this report is based on the SAP 2012 and SBEM 5.6 methods, with amended heating system efficiencies and carbon emission factors, it is expected that any new standards for 2020 will be based on analysis using SAP10 or a successor method and an updated SBEM version.

Appendices

Appendix A - Standards comparison

Tables A.1 and A.2 summarise the key findings of the review of existing energy and climate change mitigation standards.

Table A.1 Comparison of selected energy and climate change mitigation standards (table 1 of 2)

Attributes	Part L 2013	GLA (draft) London Plan targets	Energiesprong	Passivhaus	Passivhaus Plus
Level of ambition and targets					
Metrics used	$kgCO_2$ per m^2 floor area per annum associated with regulated delivered energy	$kgCO_2$ per m^2 floor area per annum associated with regulated delivered energy	Space heating demand per m^2 floor area per annum Net delivered energy over the year	Space heating and cooling demand per m^2 floor area per annum Total primary energy demand per m^2 per annum OR Renewable Primary Energy demand (PER)[109] $kWh/m^2/yr$ Maximum air changes per hour at 50 Pascals pressure	Space heating delivered energy $kWh/m^2/yr$, Total Renewable Primary Energy demand (PER) $kWh/m^2/yr$ Renewable energy generation per m^2 of building footprint $kWh(PER)/m^2(ground)/yr$ Maximum air changes per hour at 50 Pascals pressure
Building uses targets apply to	Domestic & Non-domestic	Domestic & Non-domestic	Domestic	Domestic & Non-domestic	Domestic & Non-domestic

[109] The PER factor is determined by the simultaneity of available energy resources and the energy demand. This dictates how much energy needs to be temporarily stored before it is used and the losses that are incurred in the process (for example, during short-term storage or inter-seasonal storage). For more detail refer https://passipedia.org/certification/passive_house_categories/per

Attributes	Part L 2013	GLA (draft) London Plan targets	Energiesprong	Passivhaus	Passivhaus Plus
Overall target values	Based on notional building with similar built form	35% improvement in on-site CO_2 emissions relative to Part L 2013; based on notional building	Space heating demand <30kWh/m^2/yr Net zero delivered energy over the year	Space heating demand <15kWh/m^2/yr, plus PER <60kWh/m^2/yr (or PE<120kWh/m^2/yr under transitional arrangements)	Space heating demand <15kWh/m^2/yr, PER <45kWh/m^2/yr and Renewable energy generation ≥60kWh/m^2/yr of building footprint
Operational performance targets?	No	No	Yes	No	No
Inclusions and exclusions for target setting (i.e. regulated and/or unregulated energy uses, cooling energy)	heating, cooling, ventilation, hot water, lighting	heating, cooling, ventilation, hot water, lighting	heating, ventilation, hot water, lighting, appliances	heating, cooling, ventilation, hot water, lighting, auxiliary electricity and electrical appliances	heating, cooling, ventilation, hot water, lighting, auxiliary electricity and electrical appliances
Minimum (whole building) fabric standard	Fabric Energy Efficiency Standard (FEES) based on notional building; typically, 45-50kWh/m^2/yr for flats and 55-60kWh/m^2/yr for houses; not applicable for non-domestic	Fabric Energy Efficiency Standard (FEES) based on notional building; 10% improvement in energy efficiency for domestic and 15% for non-domestic relative to Part L (some or part of which may come from fabric improvements)	Space heating demand <30kWh/m^2/yr	Space heating demand <15kWh/m^2/yr	Space heating demand <15kWh/m^2/yr
Minimum elemental requirements for building fabric	Limiting (Indicative to achieve compliance)	As per Part L 2013	Indicative to achieve compliance	Limiting	Limiting

Attributes	Part L 2013	GLA (draft) London Plan targets	Energiesprong	Passivhaus	Passivhaus Plus
External walls	0.30 W/m²K (0.18)		0.1 W/m²K	0.15 W/m².K	0.15 W/m²K
Floor	0.25 W/m²K (0.13)		0.1 W/m²K	0.15 W/m².K	0.15 W/m²K
Roof	0.20 W/m²K (0.13)		0.1 W/m²K	0.15 W/m².K	0.15 W/m²K
Windows	2.0 W/m²K (1.4)		1.0 W/m²K	0.85 W/m².K	0.85 W/m²K
Air-tightness	10.0 m³/h.m² @50pa (5)		3.0 m³/h.m² @50pa	0.6 ach @50pa	0.6 ach @50pa
Thermal bridging	0.15 (0.05)		0.03	0.01	0.01
Minimum renewable energy requirement	No	No	No	No; however renewables will typically be required for compliance with primary energy target	>60kWh (PER)/m² (ground)/yr
Embodied carbon targets	No	No	No	No	No
Flexibility/ trade-off between fabric, renewables and/or embodied carbon targets	Assessment requires FEES compliance; compliance with target emission rate can be achieved through combination of energy efficiency and renewables	Part L Compliance to be achieved by fabric energy efficiency measures alone	Space heating target to be delivered with energy efficiency alone.	Space heating target to be delivered with energy efficiency alone; renewable energy can contribute to achieving the primary energy demand target	Space heating target to be delivered with energy efficiency alone; renewable energy can contribute to achieving the primary energy demand target
Carbon offsetting allowed	No	Yes	No	No	No
Requirements related to climate change adaptation	Simple Overheating Assessment	Overheating assessment required with future weather files (TM59)	-	Limit on hours exceeding 25°C	Limit on hours exceeding 25°C

Attributes	Part L 2013	GLA (draft) London Plan targets	Energiesprong	Passivhaus	Passivhaus Plus
Calculation methodology					
Use of 'notional' buildings for assessing compliance?	Yes	Yes	No	No	No
Occupancy assumptions	Formula based on floor area	Formula based on floor area	Not known (likely to be bespoke as targets are performance based)	Assessment based on fixed internal gain per m^2, which includes occupancy gain.	Assessment based on fixed internal gain per m^2, which includes occupancy gain.
Weather data	Normalised to East Pennines region	Normalised to East Pennines region	Not known (likely to be bespoke as targets are performance based)	Climate data for all global regions except Antarctica.	Climate data for all global regions except Antarctica.
Technological approaches for compliance					
Limitations on using certain heating, cooling or ventilation systems for compliance?	Limiting system efficiencies - Domestic Building Services Compliance Guide	Limiting system efficiencies - Domestic Building Services Compliance Guide	-	Limitations on SFP and heat exchanger efficiency of MVHR unit. (<0.45Wh/m^3 and >75% respectively)	Limitations on SFP and heat exchanger efficiency of MVHR unit. (<0.45Wh/m^3 and >75% respectively)
Specific technologies mandated?	No	No	No	No	No
Encourages MMC and/or prefabricated building solutions?	No	No	Not specified but is implicit from case studies to date	No	No
Level of rigour and quality assurance					

Attributes	Part L 2013	GLA (draft) London Plan targets	Energiesprong	Passivhaus	Passivhaus Plus
Quality assurance process mandated?	Certified assessors plus auditing body	Independent consultants carry out analysis plus policy officer's assessment required	Performance guarantees put in place relating to a target level of actual operational performance.	Certified assessors plus auditing body	Certified assessors plus auditing body
Certification required?	Yes	No	No	Yes	Yes
Mandatory training for certifiers/ assessors?	Yes	Yes	No	Yes	Yes

Table A.2 Comparison of selected energy and climate change mitigation standards (table 2 of 2)

Attributes	ZCH Advanced EE spec with ASHPs (Scenario 7)	Zero carbon (previously Code 6) target	BREEAM 2014 New Construction energy target for 'Outstanding' rating	Proposed NZEB Definition - Netherlands	Proposed NZEB Definition - Denmark
Level of ambition and targets					
Metrics used	Elemental standard with defined fabric elemental values (U-values air-permeability at @50Pa, thermal bridging y-value)	$kgCO_2$ per m^2 floor area per annum associated with total (regulated and unregulated) delivered energy	Energy performance ratio (EPR) derived from a combination of heating and cooling energy demand, primary energy consumption and building CO_2 emissions	Energy Performance Coefficient (EPC) for annual primary energy against a 2011 baseline	Primary energy consumption in $kWh/m^2/yr$
Building uses targets apply to	Domestic	Domestic	Non-domestic	Domestic and Non-domestic	Domestic and Non-domestic
Overall target values	See minimum elemental requirements in rows below	Net zero CO_2 emissions over the year from both regulated and unregulated energy uses	Energy performance ratio >0.6 with zero net regulated CO_2 emissions as the upper threshold of the standard	EPC of close to zero (requirements for EPC $\leq$0.4 for residential buildings since 2015)	$<20kWh/m^2/yr$ for domestic $<25kWh/m^2/yr$ for non-domestic
Operational performance targets?	No	No	No	No	No
Inclusions and exclusions for target setting (i.e. regulated and/or unregulated energy uses, cooling energy)	heating, cooling, ventilation, hot water, lighting	heating, cooling, ventilation, hot water, lighting, unregulated energy uses (cooking and appliances)	heating, cooling, ventilation, hot water, lighting	heating, cooling, ventilation, hot water, lighting	heating, cooling, ventilation, hot water, lighting

Attributes	ZCH Advanced EE spec with ASHPs (Scenario 7)	Zero carbon (previously Code 6) target	BREEAM 2014 New Construction energy target for 'Outstanding' rating	Proposed NZEB Definition - Netherlands	Proposed NZEB Definition - Denmark
Minimum (whole building) fabric standard	Elemental values (see values in cells below)	Fabric Energy Efficiency Standard (FEES) of <39kWh/m^2/yr for flats and <46kWh/m^2/yr for houses	None	None Limits for thermal resistance value of elements; Resistance (Rc) of >5.0 m^{2}K/W for both domestic and non-domestic buildings (effective since 2015)	Design transmission loss (W/m^2 of building envelope) of: < 3.7 for single-storey, <4.7 for two-storey, and <5.7 for three storeys or more Building envelope area excludes windows and doors
Minimum elemental requirements for building fabric	Required values	As per Part L 2013	-		
External walls	0.15 W/m^{2}K				
Floor	0.15 W/m^{2}K				
Roof	0.11 W/m^{2}K				
Windows	0.8 W/m^{2}K			<1.65 W/m^{2}K for both domestic and non-domestic buildings (since 2013)	Energy balance of windows: 0 kWh/m^2/yr (+10kWh/m^2/yr for roof lights)
Air-tightness	1.0 m^3/h.m^2 @50pa				0.5 l/s per m^2 of heated floor area at 50pa pressure difference
Thermal bridging	0.04 W/m^{2}K				

Attributes	ZCH Advanced EE spec with ASHPs (Scenario 7)	Zero carbon (previously Code 6) target	BREEAM 2014 New Construction energy target for 'Outstanding' rating	Proposed NZEB Definition - Netherlands	Proposed NZEB Definition - Denmark
Minimum renewable energy requirement	No	No; renewables will however be required for compliance with net zero carbon target	No	No	No; renewables will however be required for compliance with target
Embodied carbon targets	No	No	Mat01 assesses the life cycle impacts of construction materials, which includes embodied carbon calculations. Compliance with this criterion is not mandatory and does not include specific embodied carbon targets.	Not as part of NZEB definition; Netherlands, Building Decree 2012 (Article 5.9 on sustainable construction) has required LCA calculations covering GHGs and resource depletion for new homes and non-domestic buildings over $100m^2$ since 2013.	Not as part of NZEB definition
Flexibility/ trade-off between fabric, renewables and/or embodied carbon targets	Not applicable	Assessment requires FEES compliance; compliance with net zero target can be achieved through combination of energy efficiency and renewables	Energy performance ratio can be achieved by mix of energy efficiency and renewable technologies	Yes; compliance with target can be achieved through combination of energy efficiency, renewables and fossil fuel generation, subject to minimum fabric performance requirements being met.	Yes; compliance with target can be achieved through combination of energy efficiency, renewables and fossil fuel generation, subject to minimum fabric performance requirements being met.
Carbon offsetting allowed	No	No	No	No	No

Attributes	ZCH Advanced EE spec with ASHPs (Scenario 7)	Zero carbon (previously Code 6) target	BREEAM 2014 New Construction energy target for 'Outstanding' rating	Proposed NZEB Definition - Netherlands	Proposed NZEB Definition - Denmark
Requirements related to climate change adaptation	No	No	A range of criteria take into account future thermal comfort, flood risk and resilience of structure, fabric, building services and renewables installation to climate change. Compliance is not mandatory for an 'Outstanding' rating.	No/ Not explicit in NZEB plan	Limit on number of hours exceeded above 26°C annually.
Calculation methodology					
Use of 'notional' buildings for assessing compliance?	No	Yes	Yes	Yes	No
Occupancy assumptions	Not applicable	Formula based on floor area	Uses Part L compliance tools and assumptions	Prescribed standard assumptions	Prescribed standard assumptions
Weather data	Not applicable	Normalised to East Pennines region	Uses Part L compliance tools and assumptions	Prescribed standard climatic conditions	Prescribed standard climatic conditions (uses single climate zone)
Technological approaches for compliance					
Limitations on using certain heating, cooling or ventilation systems for compliance?	Yes, minimum performance requirements for air source heat pumps (ASHPs) and mechanical ventilation with heat recovery (MVHR)	Limiting system efficiencies - Domestic Building Services Compliance Guide	-	Minimum efficiency/ system requirements for heating, ventilation, air-conditioning and lighting	Minimum efficiency/ system requirements for heating, ventilation, air-conditioning and lighting

Attributes	ZCH Advanced EE spec with ASHPs (Scenario 7)	Zero carbon (previously Code 6) target	BREEAM 2014 New Construction energy target for 'Outstanding' rating	Proposed NZEB Definition - Netherlands	Proposed NZEB Definition - Denmark
Specific technologies mandated?	Yes, ASHPs and MVHR	No	No	No	Solar thermal mandatory for new buildings with domestic hot water consumption above 2000 litres.
Encourages MMC and/or prefabricated building solutions?	No	No	No	No	No
Level of rigour and quality assurance					
Quality assurance process mandated?	Assumed same as Part L	Assumed same as Part L	Certified assessors plus auditing body	Certified assessors plus auditing body	Certified assessors plus auditing body
Certification required?	Assumed same as Part L	Assumed same as Part L	Yes	Yes	Yes
Mandatory training for certifiers/ assessors?	Assumed same as Part L	Assumed same as Part L	Yes	Yes	Yes

Appendix B - Building archetypes

Table B.1 describes the key dimensional information for each domestic building archetype, Table B.2 provides this information for the non-domestic archetypes.

Table B.1 Area and storey heights of domestic archetypes

	Detached	Semi	1B Flat - Ground	1B Flat - Mid	1B Flat - Top	2B Flat - Ground	2B Flat - Mid	2B Flat - Top
AREAS (sqm)								
Party wall	0.0	41.8	28.1	28.1	28.1	29.2	29.2	29.2
Exposed wall	156.3	93.8	18.0	18.0	18.0	41.3	41.3	41.3
Semi-exposed wall	0.0	0.0	24.0	24.0	24.0	12.1	12.1	12.1
Roof - Main	58.1	41.8	0.0	0.0	50.0	0.0	0.0	70.1
Roof - Bay window	0.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0
Floor	58.9	42.6	50.0	0.0	0.0	70.1	0.0	0.0
TFA	117.1	84.4	50.0	50.0	50.0	70.1	70.1	70.1
Total window area	26.2	14.6	9.8	9.8	9.8	13.8	13.8	13.8
Total door area	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
HEIGHTS (m)								
Storey	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4

Table B.2 Area and storey heights of non-domestic archetypes

	NV Office	AC Office
AREAS (sqm)		
Party wall	0.0	0.0
Exposed wall (excl glazing)	1,008	8,000
Roof - Main	1,500	3,000
Ground Floor	1,500	3,000
TFA	4,500	30,000
Glazing ratio	40%	80%
Total window area	672	6,400
HEIGHTS (m)		
Storey	3.6	3.6

Baseline specifications

The reference specification for the house types and low-rise apartments are based on a masonry cavity wall construction method with a pitched roof and suspended concrete ground floor. High rise apartments are based on a concrete frame with solid floors and flat roofing. External walls would comprise a masonry inner leaf, insulation and either brickwork or rainscreen cladding.

Office buildings are based on a steel frame with concrete floors and lightweight metal frame external walls with insulation and a rainscreen cladding.

Specifications of each construction type are shown in tables B.3 and B.4, together with the variations in performance level and any associated change specific components (eg insulation thickness). Specifications for internal elements are not included within our models as this does not impact operational energy performance, advice on typical internal specifications can be provided if it would be useful.

Table B.3 Specification of masonry buildings (houses and low-rise apartments)

Element	Specification
External walls U values from 0.21 to 0.12 W/m²K	12.5mm plasterboard on dabs (25mm overall) 100mm AAC blockwork - 0.15W/m K (houses) and 0.19W/m K (flats) Insulation (125mm mineral wool to 150mm PUR) 102.5mm facing brickwork Cavity (125mm to 150mm); stainless steel wall ties 2.5/m² Cavity closers Cavity trays Lintols
Party walls U value 0.0 W/m²K	13mm plaster 100mm 4N/mm² AAC blockwork (0.16WmK) 75mm glass wool insulation 100mm 4N/mm² AAC blockwork (0.16WmK) 75mm cavity; stainless steel wall ties 2.5/m²
Ground floor U values from 0.15 to 0.11 W/m²K	150mm concrete beam and block floor 110mm to 180mm rigid board insulation (0.022W/m K) 75mm screed 30mm EPS insulation upstand at perimeter (0.025W/m K)
Roof U values from 0.13 to 0.11 W/m²K	Timber trusses; with 100mm ceiling joists 100mm mineral wool insulation quilt between joists (0.042 W/m K) 250mm to 300mm mineral wool insulation quilt above joists (0.042 W/m K) 12.5mm plasterboard ceiling
Windows U values from 1.2 to 0.8 W/m²K	Double or triple glazed uPVC windows with Low-E coating (soft)
Doors (external) U values from 1.2 to 1.0 W/m²K	insulated steel faced doors with no glazing (lower U value requires a thermally broken frame)

Table B.4 Specification of framed buildings (offices and high-rise apartments)

Element	Specification
Frame	▪ In situ concrete frame (high rise apartments) ▪ Steel frame (offices)
External walls U values from 0.30 to 0.15 W/m²K	Cavity walls as per houses / low rise apartments (see Table 3) Rainscreen cladding on light metal frame ▪ Rainscreen ▪ 110mm to 240mm mineral wool (λ=0.037) or 65mm to 150mm PIR insulation (λ=0.022) on: ▪ 12mm Cementitious Particle Board (CPB) OR 12mm Orientated Strand Board

	▪ Vapour Control Layer ▪ 15mm Plasterboard
Party walls U value 0.0 W/m²K	▪ 13mm plaster ▪ 100mm 4N/mm² AAC blockwork (0.16WmK) ▪ 75mm glass wool insulation ▪ 100mm 4N/mm² AAC blockwork (0.16WmK) ▪ 75mm cavity; stainless steel wall ties 2.5/m²
Ground floor U values from 0.25 to 0.10 W/m²K	▪ Concrete screed (70mm) ▪ 60mm to 180mm Rigid PIR board (λ=0.022) ▪ 35mm edge insulation (1000 wide along perimeter, rigid PU (λ=0.022))
Roof U values from 0.25 to 0.10 W/m²K	▪ 140mm to 380mm rigid board insulation (0.022W/m K) ▪ Polymer WP lining ▪ Deck (single ply, concrete, metal trough) ▪ Vapour Control Layer
Windows U values from 1.8 to 0.8 W/m²K	▪ Double or triple glazed uPVC or timber windows with air, argon, argon + low-E coating and krypton and low-E coating

Appendix C - Improvement measures and heating / hot water demand

Table C.1 to C.6 summarise the packages of improvement measures modelled for each building archetype. Table C.7 summarises the heating and hot water demand of each building archetype at with different specifications and heating systems.

Table C.1 Improvement measures for detached house

Building Element Description		New build standard							Retrofit specific standard*	
		Part L Notional	35kWh/m²/yr – Natural Ventilation	35kWh/m²/yr – Heat Recovery	30kWh/m²/yr	25kWh/m²/yr	20kWh/m²/yr	15kWh/m²/yr	20kWh/m²/yr - retro	15kWh/m²/yr -retro
Walls	Exposed (W/m².K)	0.18	0.15	0.18	0.17	0.15	0.15	0.13	0.14	0.13
	Semi exposed (W/m².K)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Floors	Ground Floor (W/m².K)	0.13	0.11	0.15	0.11	0.11	0.11	0.11	0.13	0.13
Roofs	Exposed Roof (W/m².K)	0.13	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
	Bay Window Roof (W/m².K)	0.13	0.13	0.2	0.13	0.13	0.11	0.11	0.11	0.11
Doors	U-value (W/m².K)	1.0	1.0	1.2	1.0	1.0	1.0	1.0	1.0	1.0
Windows	U-value (W/m².K)	1.4	0.8	1.4	1.2	0.8	0.8	0.8	0.8	0.8
Ventilation	Type	Nat Vent		MVHR						
Air Permeability	(m³/h.m² @50pa)**	5.0	3.0	3.0	3	3.0	2	1.0	3	1.0
Thermal Bridging	Y-value	0.05	0.02	0.05	0.05	0.05	0.04	0.04	0.04	0.04

*These specifications were amended to avoid the need to improve wall U values as part of a retrofit. They still achieve within 1kWh/m²/yr of the target performance standard.

** Rounded up to nearest whole number

Table C.2 Improvement measures for semi-detached house

Building Element Description		New build standard						Retrofit specific standard*	
		Part L Notional	35kWh/m²/yr	30kWh/m²/yr	25kWh/m²/yr	20kWh/m²/yr	15kWh/m²/yr	20kWh/m²/yr - retro	15kWh/m²/yr -retro
Walls	Exposed (W/m².K)	0.18	0.18	0.18	0.16	0.15	0.21	0.15	0.13
	Semi exposed (W/m².K)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Floors	Ground Floor (W/m^2.K)	0.13	0.15	0.13	0.12	0.11	0.11	0.13	0.13
Roofs	Exposed Roof (W/m^2.K)	0.13	0.11	0.13	0.11	0.11	0.11	0.11	0.11
	Bay Window Roof (W/m^2.K)	0.13	0.2	0.2	0.15	0.13	0.13	0.13	0.11
Doors	U-value (W/m^2.K)	1.0	1.2	1.0	1.0	1.0	1.0	1.0	1.0
Windows	U-value (W/m^2.K)	1.4	1.2	1.4	1.2	0.8	0.8	0.8	0.8
Ventilation	Type	Nat Vent		MVHR					
Air Permeability	(m^3/h.m^2 @50pa)**	5.0	5.0	3	3.0	2	1.0	3	1.0
Thermal Bridging	Y-value	0.05	0.04	0.05	0.05	0.04	0.04	0.04	0.04

*These specifications were amended to avoid the need to improve wall U values as part of a retrofit. They still achieve within 1kWh/m^2/yr of the target performance standard.
** Rounded up to nearest whole number

Table C.3 Improvement measures for small flat

Building Element Description		New build standard						Retrofit specific standard*	
		Part L Notional	35kWh/m^2/yr*	30kWh/m^2/yr*	25kWh/m^2/yr*	20kWh/m^2/yr	15kWh/m^2/yr	20kWh/m^2/yr - retro	15kWh/m^2/yr -retro
Walls	Exposed (W/m^2.K)	0.18				0.18	0.18		
	Semi exposed (W/m^2.K)	0.21				0.21	0.21		
Floors	Ground Floor (W/m^2.K)	0.13				0.15	0.11		
Roof	Exposed Roof (W/m^2.K)	0.13				0.11	0.11		
Doors	U-value (W/m^2.K)	1.0				1.4	1,4		
Windows	U-value (W/m^2.K)	1.4				1.4	1.4		
Ventilation	Type	Nat Vent				MVHR			
Air Permeability	(m^3/h.m^2 @50pa)**	5.0				4.0	4.0		
Thermal Bridging	Y-value	0.05				0.15	0.06		

*Not used for this archetype.
** Rounded up to nearest whole number

Table C.4 Improvement measures for large flat

Building Element Description		New build standard						Retrofit specific standard*	
		Part L Notional	35kWh/m^2/yr*	30kWh/m^2/yr*	25kWh/m^2/yr*	20kWh/m^2/yr	15kWh/m^2/yr	20kWh/m^2/yr - retro	15kWh/m^2/yr -retro
Walls	Exposed (W/m^2.K)	0.18			0.13	0.18	0.18		
	Semi exposed (W/m^2.K)	0.21			0.13	0.21	0.21		
Floors	Ground Floor (W/m^2.K)	0.13			0.11	0.15	0.11		
Roof	Exposed Roof (W/m^2.K)	0.13			0.11	0.11	0.11		
Doors	U-value (W/m^2.K)	1.0			1.0	1.4	1.4		
Windows	U-value (W/m^2.K)	1.4			1.2	1.2	1.2		
Ventilation	Type	Nat Vent			Nat Vent	MVHR			
Air Permeability	(m^3/h.m^2 @50pa)**	5.0			4.0	5.0	3.0		
Thermal Bridging	Y-value	0.05			0.07	0.1	0.1		

*Not used for this archetype.
** Rounded up to nearest whole number

Table C.5 Improvement measures for naturally ventilated office

Building Element Description		Part L (2013)	15% Improvement	20% improvement	DH-25% Improvement
External Wall 1	U-value, W/m^{2}K	0.26	0.26	0.18	0.15
Ground Floor (Ground Contact)	U-value, W/m^{2}K	0.22	0.22	0.15	0.15
Roof	U-value, W/m^{2}K	0.18	0.18	0.15	0.12
Windows	U-value, W/m^{2}K	1.60	1.60	1.40	1.20
	g-value	0.40	0.40	0.40	0.40
Ventilation	Type	Nat Vent	Nat Vent	Nat Vent	Nat Vent
Air Permeability	m^3/h.m^2 @50Pa*	3.0	3.0	3.0	3.0
Lighting	Lumens per circuit watt	65	95	95	95

* Rounded up to nearest whole number

Table C.6 Improvement measures for air-conditioned office

Building Element Description		Part L (2013)	15% Improvement	20% improvement	DH-25% Improvement
External Wall	U-value, W/m^{2}K	0.26	0.26	0.18	0.15
Ground Floor	U-value, W/m^{2}K	0.22	0.22	0.22	0.15

Roof	U-value, W/m²K	0.18	0.18	0.18	0.15
Windows	U-value, W/m²K	1.60	1.60	1.40	1.00
	g-value	0.40	0.40	0.40	0.40
Ventilation	Type	A/C	A/C	A/C	A/C
Air Permeability	m³/h.m² @50Pa*	3.0	3.0	3.0	3.0
Lighting	Lumens per circuit watt	65	95	95	95
* Rounded up to nearest whole number					

Table C.7 Space heating and hot water demand in each building archetype

	Space heating demand	Domestic hot water demand	Ratio (heat domestic hot water)
Detached House			
G-Part L Notional	43.74	18.82	2.32
G-35-NV	34.84	18.57	1.88
G-35-HR	34.68	18.47	1.88
G-30	29.52	18.47	1.60
G-25	24.71	18.47	1.34
G-20	19.73	18.47	1.07
G-15	14.85	18.47	0.80
ASHP-Part L Not	43.97	18.47	2.38
ASHP-35-NV	34.93	19.02	1.84
ASHP-35-HR	31.39	18.47	1.70
ASHP-30	27.14	18.47	1.47
ASHP-25	24.80	18.47	1.34
ASHP-20	19.81	18.47	1.07
ASHP-15	14.93	18.47	0.81
Semi-detached House			
G-Base Case	36.89	24.30	1.52
G-Part L Notional	40.16	24.30	1.65
G-NHBC	44.57	24.30	1.83
G-35	34.75	24.30	1.43
G-30	29.35	24.23	1.21
G-25	24.24	24.23	1.00
G-20	18.89	24.23	0.78
G-15	14.57	24.23	0.60
ASHP-Part L Not	38.64	24.23	1.59
ASHP-35	34.75	24.30	1.43
ASHP-30	29.48	24.23	1.22
ASHP-25	24.36	24.23	1.01

	Space heating demand	Domestic hot water demand	Ratio (heat domestic hot water)
ASHP-20	19.01	24.23	0.78
ASHP-15	14.68	24.23	0.61
Small Flat			
G-Base Case	26.02	32.31	0.81
G-Part L Notional	27.93	32.31	0.86
G-NHBC	30.26	32.31	0.94
G-20	19.40	35.18	0.55
G-15	14.70	35.18	0.42
ASHP-Part L Not	27.93	32.31	0.86
ASHP-20	19.40	35.18	0.55
ASHP-15	14.70	35.18	0.42
Large Flat			
G-Base Case	33.15	27.16	1.22
G-Part L Notional	32.89	27.16	1.21
G-NHBC	37.20	27.16	1.37
G-20	19.16	27.62	0.69
G-15	14.75	27.62	0.53
ASHP-Part L Not	32.08	27.62	1.16
ASHP-20	19.29	27.62	0.70
ASHP-15	14.88	27.62	0.54
Naturally ventilated office			
G - Part L (2013)	15.87	2.53	6.27
G-15% Improvement	17.94	2.64	6.79
G-20% Improvement	14.29	2.64	5.41
G-25% Improvement	12.49	2.64	4.73
ASHP - Part L (2013)	16.58	2.64	6.29
ASHP-15% Improvement	18.74	2.64	7.11
ASHP - 20% improvement	14.93	2.64	5.66
ASHP-25% Improvement	12.19	2.64	4.62
Air-conditioned office			
G - Part L (2013)	3.01	2.48	1.21
G-15% Improvement	3.82	2.56	1.49
G-20% Improvement	2.70	2.56	1.06
G-25% Improvement	0.93	2.57	0.36
ASHP - Part L (2013)	3.09	2.56	1.21
ASHP-15% Improvement	3.80	2.56	1.48
ASHP - 20% improvement	2.69	2.56	1.05
ASHP-25% Improvement	0.85	2.56	0.33

Appendix D - Summary of cost information

Tables D1 to D.3 contain the cost information used within modelling for new and existing domestic archetypes.

D.1 New build cost data for domestic buildings - fabric

Element	Specification	Unit	New cost (£/m^2)	Retrofit cost (£m^2)
External Wall – Traditional masonry and mineral wool, retrofit with PIR				
External Wall (MW)	0.21	W/m².K	219	
External Wall (MW)	0.18	W/m².K	221	Base case
External Wall (MW)	0.17	W/m².K	221	97
External Wall (MW)	0.16	W/m².K	221	98
External Wall (MW)	0.15	W/m².K	224	100
External Wall (MW)	0.14	W/m².K	225	102
External Wall (MW)	0.13	W/m².K	230	107
Semi-exposed wall (MW)				
Semi-exposed wall	0.21	W/m².K	146	
Semi-exposed wall	0.18	W/m².K	148	
Semi-exposed wall	0.16	W/m².K	148	
Semi-exposed wall	0.15	W/m².K	151	
Semi-exposed wall	0.14	W/m².K	152	
Semi-exposed wall	0.13	W/m².K	157	
Semi-exposed wall	0.12	W/m².K	158	
Ground / Exposed Floor				
Ground / Exposed Floor	0.18	W/m².K	140	
Ground / Exposed Floor	0.16	W/m².K	143	
Ground / Exposed Floor	0.15	W/m².K	146	
Ground / Exposed Floor	0.14	W/m².K	149	
Ground / Exposed Floor	0.13	W/m².K	152	
Ground / Exposed Floor	0.12	W/m².K	154	
Ground / Exposed Floor	0.11	W/m².K	157	
Exposed Roof - Insulation at Joists				
Exposed Roof	0.18	W/m².K	175	
Exposed Roof	0.16	W/m².K	176	
Exposed Roof	0.15	W/m².K	185	
Exposed Roof	0.14	W/m².K	185	
Exposed Roof	0.13	W/m².K	185	Base case
Exposed Roof	0.12	W/m².K	186	15
Exposed Roof	0.11	W/m².K	187	15
Doors				
Doors	1.4	W/m².K	240	Base case

Element	Specification	Unit	New cost (£/m^2)	Retrofit cost (£m^2)
Doors	1.2	W/m^2.K	270	763
Doors	1.1	W/m^2.K	300	
Doors	1	W/m^2.K	330	
Doors	0.8	W/m^2.K	390	908
Windows				
Windows	1.4	W/m^2.K	240	Base case
Windows	1.3	W/m^2.K	270	
Windows	1.2	W/m^2.K	300	346
Windows	1	W/m^2.K	330	
Windows	0.8	W/m^2.K	360	436
Design Air Permeability				
Design Air Permeability	5	m^3/hm^2 at 50Pa	2	
Design Air Permeability	4	m^3/hm^2 at 50Pa	4	
Design Air Permeability	3	m^3/hm^2 at 50Pa	5	
Design Air Permeability	2	m^3/hm^2 at 50Pa	6	
Design Air Permeability	1	m^3/hm^2 at 50Pa	8	

All fabric items deemed to have life expectancy of +60 years except windows and doors for which a lifespan of 30 years is used. Energy efficiency rating should have no impact on the maintenance costs associated with fabric items.

D.2 New build cost data for domestic buildings - services

Element	Specification		New cost (£/home)	Retrofit cost (£home)
Ventilation				
Ventilation	Nat Vent		480	
MVHR unit				
MVHR unit	Detached		820	1250
MVHR unit	Semi-Detached		820	1250
MVHR unit	Small Flat		720	1000
MVHR unit	Large Flat		720	1000
MVHR ducting and installation				
MVHR ducting and installation	Detached		1540	3340
MVHR ducting and installation	Semi-Detached		1390	2865
MVHR ducting and installation	Small Flat		1115	2090
MVHR ducting and installation	Large Flat		1190	2340
Gas Boiler				
Gas Boiler	Detached	System	2338	
Gas Boiler	Semi-Detached	Combi	2562	
Gas Boiler	Small Flat	Communal	7452*	

Element	Specification		New cost (£/home)	Retrofit cost (£home)
Gas Boiler	Large Flat	Combi	2430	
Gas Boiler Sundries (controls and distribution)				
Gas Boiler Sundries	Detached		2747	
Gas Boiler Sundries	Semi-Detached		2006	
Gas Boiler Sundries	Small Flat		1123	
Gas Boiler Sundries	Large Flat		1692	
ASHP				
ASHP	Detached		3794	3794
ASHP	Semi-Detached		3794	3794
ASHP	Small Flat		3033	2154
ASHP	Large Flat		3033	3033
ASHP Sundries (controls and distribution, etc)				
ASHP Sundries	Detached		2902	568
ASHP Sundries	Semi-Detached		2161	568
ASHP Sundries	Small Flat		1123	568
ASHP Sundries	Large Flat		1847	568
Gas connection				
Gas connection	Single property (outside London)		346	
Gas connection	Single property (London)		743	
Gas connection	Development of 10 properties		988	
Gas connection	Development of 100 properties		1076	
District Heat Network				
District HP - Houses	Detached		3430	3430
District HP - Houses	Semi-Detached		3430	3430
District HP - Flats	Small Flat		6085	3430
District HP - Flats	Large Flat		5285	3430
District Heat Pump - Connection				
Connection - Houses	Detached		1000	1543
Connection - Houses	Semi-Detached		1000	1543
Connection - Flats	Small Flat		1200	1543
Connection - Flats	Large Flat		1200	1543
Communal Heat Pump - Flats				
Communal HP - Flats	Small Flat		8406	2154
Communal Heat Pump - Flats - Sundries				
Connection - Flats	Small Flat		1123	
Connection - Flats	Large Flat		868	
Standard Radiators				
Standard Radiators	Detached	£58.59	879	

Element	Specification		New cost (£/home)	Retrofit cost (£home)
Standard Radiators	Semi-Detached	£58.59	586	
Standard Radiators	Small Flat	£58.59	293	
Standard Radiators	Large Flat	£58.59	410	
Larger Radiators				
Larger Radiators	Detached	£90.00	1350	3997
Larger Radiators	Semi-Detached	£90.00	900	2748
Larger Radiators	Small Flat	£90.00	450	1499
Larger Radiators	Large Flat	£90.00	630	1999
Hot water store				
Unvented indirect cylinder	Detached	300 litres	1229	1622
Unvented indirect cylinder	Semi-Detached	210 litres	1132	1524
Unvented indirect cylinder	Small Flat	210 litres	1132	1524
Unvented indirect cylinder	Large Flat	210 litres	1132	1524
Thermal store for heating system				
Thermal Store	Detached	500 litres	4352	4587
Thermal Store	Semi-Detached	350 litres	2224	2459
Thermal Store	Small Flat	210 litres	1977	2212
Thermal Store	Large Flat	350 litres	2224	2459
Battery Storage				
Battery Storage	All	2kW	2000	2393
External Shading				
External Shading	Detached		1749	
External Shading	Semi-Detached		982	
External Shading	Small Flat		659	
External Shading	Large Flat		928	

Table D.3 summarises the life expectancy of each building services and any associated variations in maintenance costs related to their energy efficiency characteristics.

D.3 Life expectancy and maintenance costs

Element	Life expectancy	Annual maintenance costs (£ pa)
Gas boiler	15	100
ASHP	18	75
Heat interface unit	18	75
Radiators (standard and large)	60	0
Hot water store	20	0
Battery (Li-ion)	10	0
MVHR	20	25

Appendix E - Cost projections

Cost projections were generated for six technology types with other technologies considered 'mature' and therefore no longer subject to material learning effects. The modelled learning effects used in the central scenario are shown in Figure 4.6, source information and modelling assumptions are described below.

Triple glazed windows

Direct cost projections taken from a research study[110], which projects costs through to 2030 and has provided a reasonable correlation with costs experienced in the period between 2010 and 2018.

Heat interface units

Future cost projections sourced from published research[111] for 2025 (6.9%) and 2050 (15.2%) with linear interpolation of reductions in each year.

LED Lighting

Future cost projections sourced from published research[112] for LED build prices and performance.

Battery storage

Future cost projection sourced from published research[113] projecting a 61% fall in the price of lithium iron phosphate-based batteries (the chemistry predominantly used for stationary non-utility battery systems) between 2017 and 2030.

ASHP

Installation and product costs for ASHP plant (excluding hot water storage and sundries such as distribution pipework and heat emitters) were calculated separately and then combined on a 40:60 ratio reflecting the current breakdown of these costs.

Installation cost trends are projected based on current UK installation rates of c19,000 units per year and high, medium low learning rates of 18%, 8% or 5%. An alternate scenario was also tested where policy support drives much higher uptake of ASHP to a level of 150,000 units per year. By 2030 the installation costs under each scenario are 91% or 78% of the 2017 cost respectively.

ASHP market projections for heat pump units are based on those published by the International Energy Agency[114] which suggest a more than six-fold increase in installed capacity up to 4,800 GWth by 2050.

The central combined cost projection for installation and product costs indicate a reduction in installed cost to around 89% of 2017 prices by 2030.

[110] Jakob, M and Madlener, R, 2004. Riding down the experience curve for energy efficient building envelopes: the Swiss case for 1970-2020. Int J. Energy Technology and Policy, Vol. 2, Nos 1/2.
[111] Carbon Trust, 2018. Estimating the cost-reduction impact of the Heat Network Investment Project on future heat networks. Information taken relates to 'interface with heat user', page 36.
[112] McKinsey, 2017. Lighting the way: Perspectives on the global lighting market.
[113] International Renewable Energy Agency, 2017. Electricity storage and renewables: Costs and markets to 2030.
[114] IEA, 2011. Technology Roadmap - Energy-Efficient Buildings - Heating and Cooling Equipment

Airtightness

Cost projections for higher levels of air tightness (below 3 m^3m^2yr) are based constant installation profile of c.10% of new homes being built to these higher levels of air tightness and resulting in a central projection of a 14% reduction in the costs of meeting this standard by 2030.

Appendix F - Cost-effectiveness results for other domestic archetypes

Detached House

Figures F.1 and F.2 show the cost-effectiveness results for the detached house with varying efficiency standards and with a gas or ASHP heating system in 2020 and 2025 respectively. Figure F.3 illustrates how the cost-effectiveness of selected specifications (Part L Notional with ASHP and 15 kWh/m[2]/yr with gas and ASHP) vary between 2020 and 2030.

Figure F.1 Cost-effectiveness results for Detached House – 2020

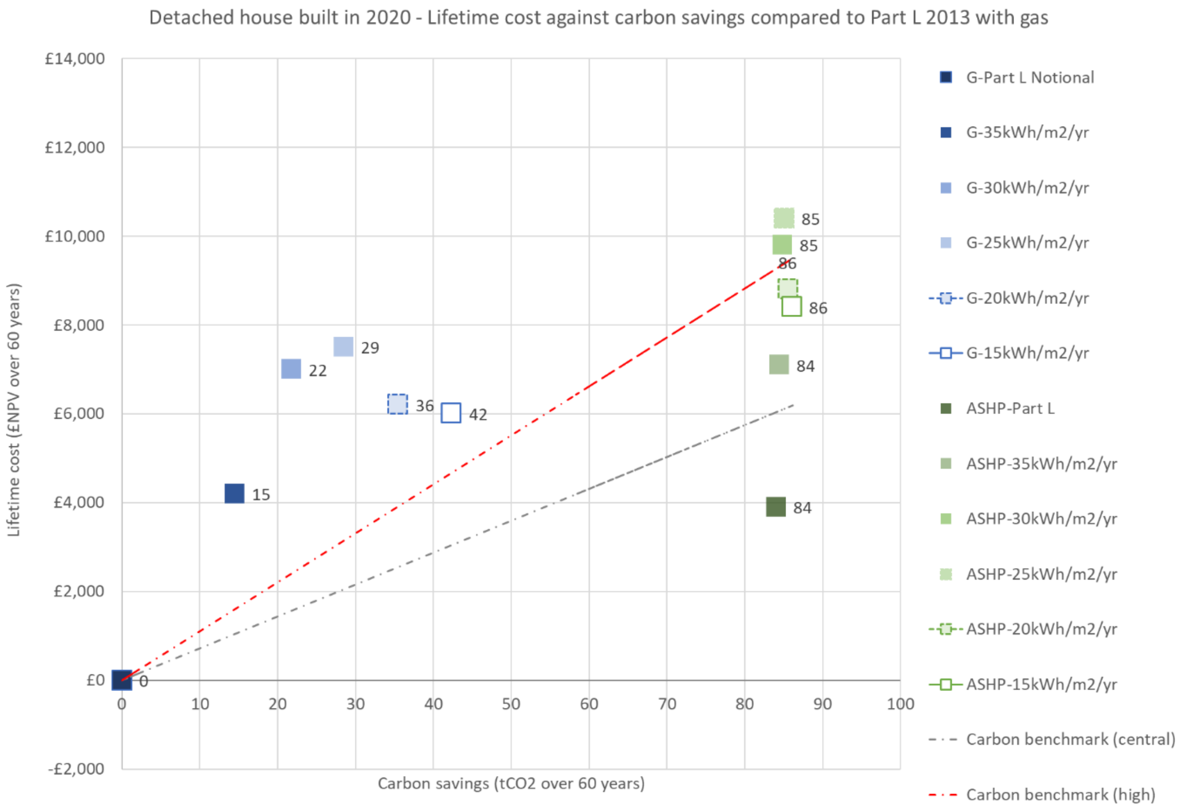


Figure F.2 Cost-effectiveness results for Detached House – 2025

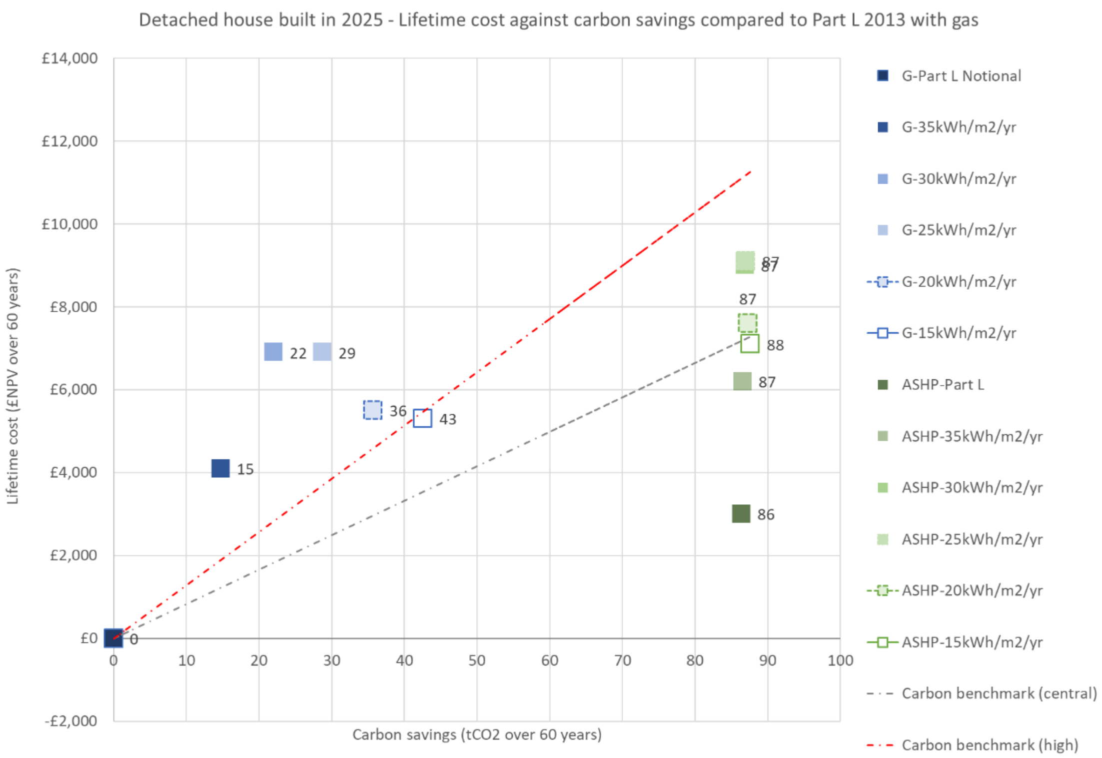
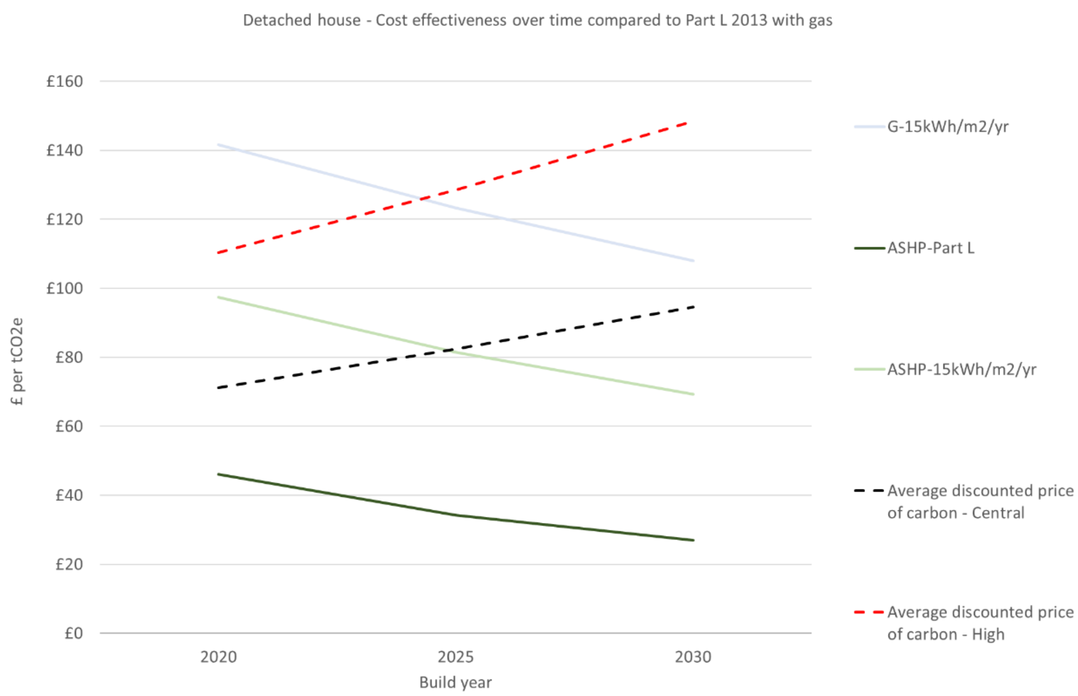


Figure F.3 Cost-effectiveness results for Detached House – 2020-2030



Small Flat

Figures F.4 and F.5 show the cost-effectiveness results for the detached house with varying efficiency standards and with a gas or ASHP heating systems in 2020 and 2025 respectively. Figure F.6 illustrates how the cost-effectiveness of selected specifications (Part L Notional with ASHP and 15 kWh/m^2/yr with gas and ASHP) vary between 2020 and 2030.

Figure F.4 Cost-effectiveness results for small flat – 2020

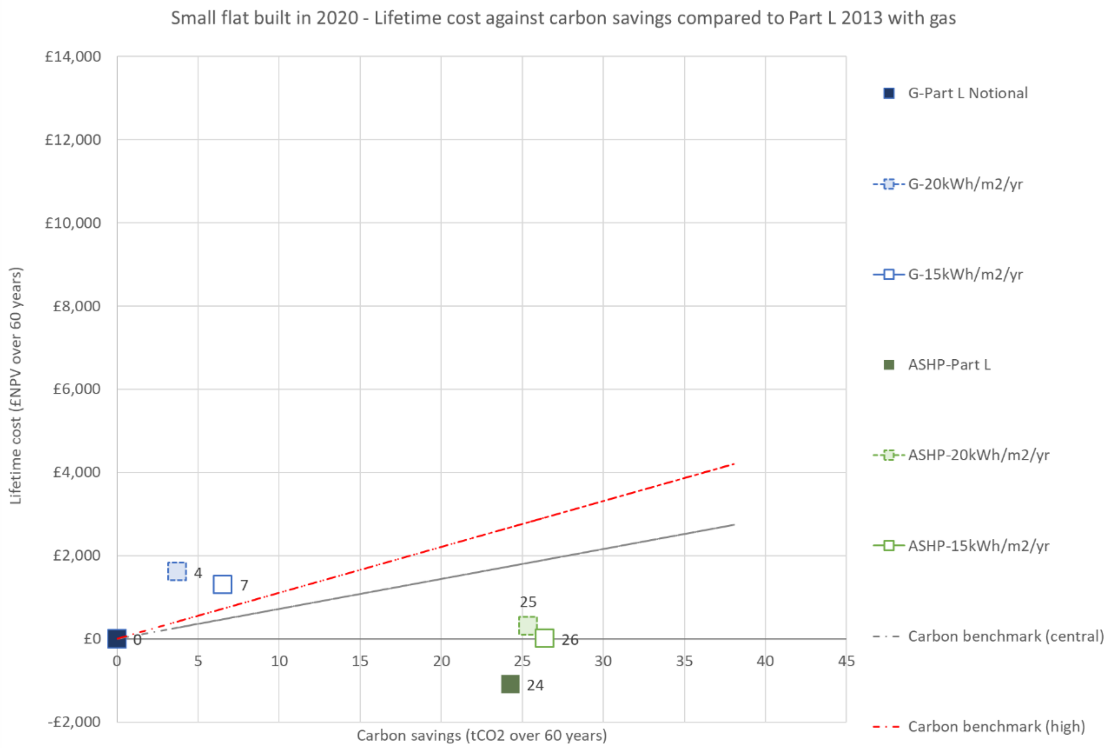


Figure F.5 Cost-effectiveness results for small flat – 2025

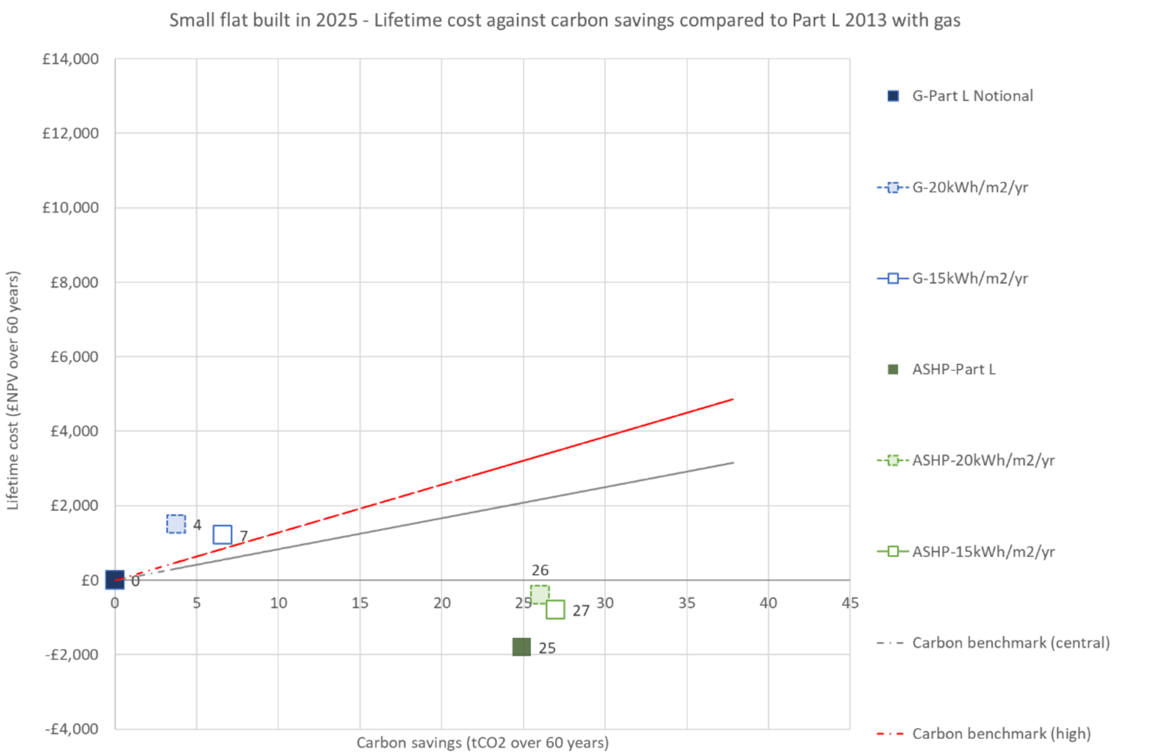
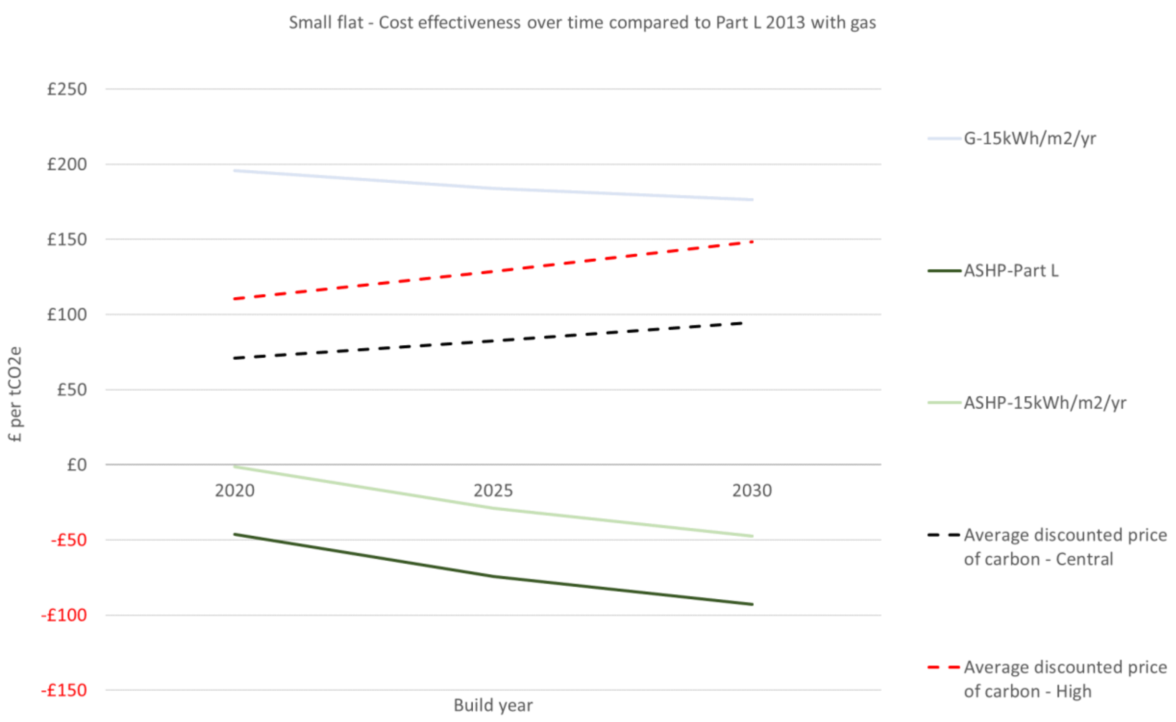


Figure F.6 Cost-effectiveness results for small flat – 2020-2030



Large Flat

Figures F.7 and F.8 show the cost-effectiveness results for the detached house with varying efficiency standards and with a gas or ASHP heating systems in 2020 and 2025 respectively. Figure F.9 illustrates how the cost-effectiveness of selected specifications (Part L Notional with ASHP and 15 kWh/m^2/yr with gas and ASHP) vary between 2020 and 2030.

Figure F.7 Cost-effectiveness results for large flat – 2020

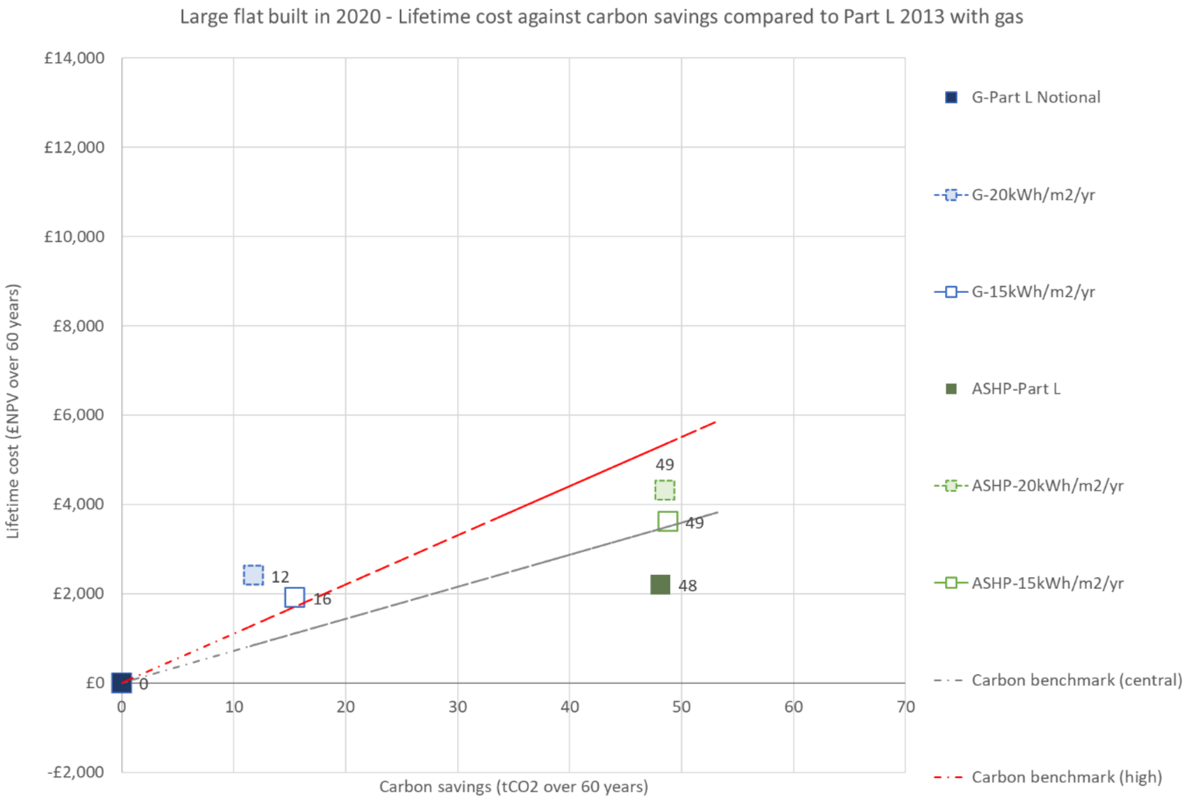


Figure F.8 Cost-effectiveness results for large flat – 2025

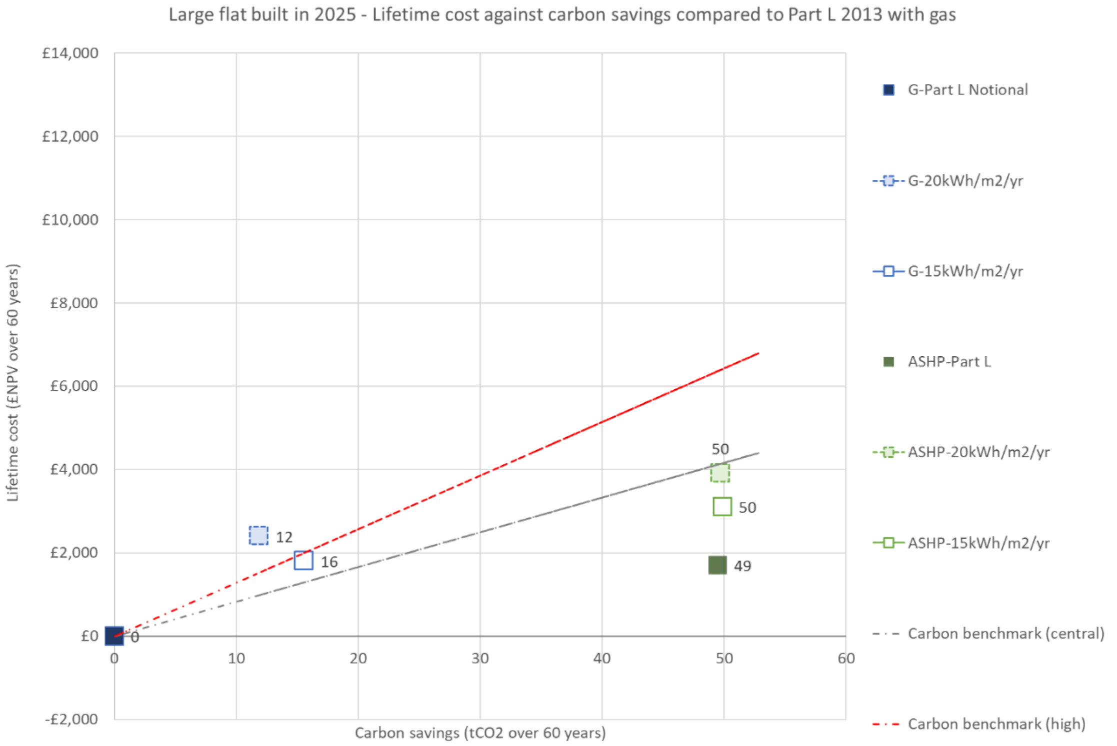
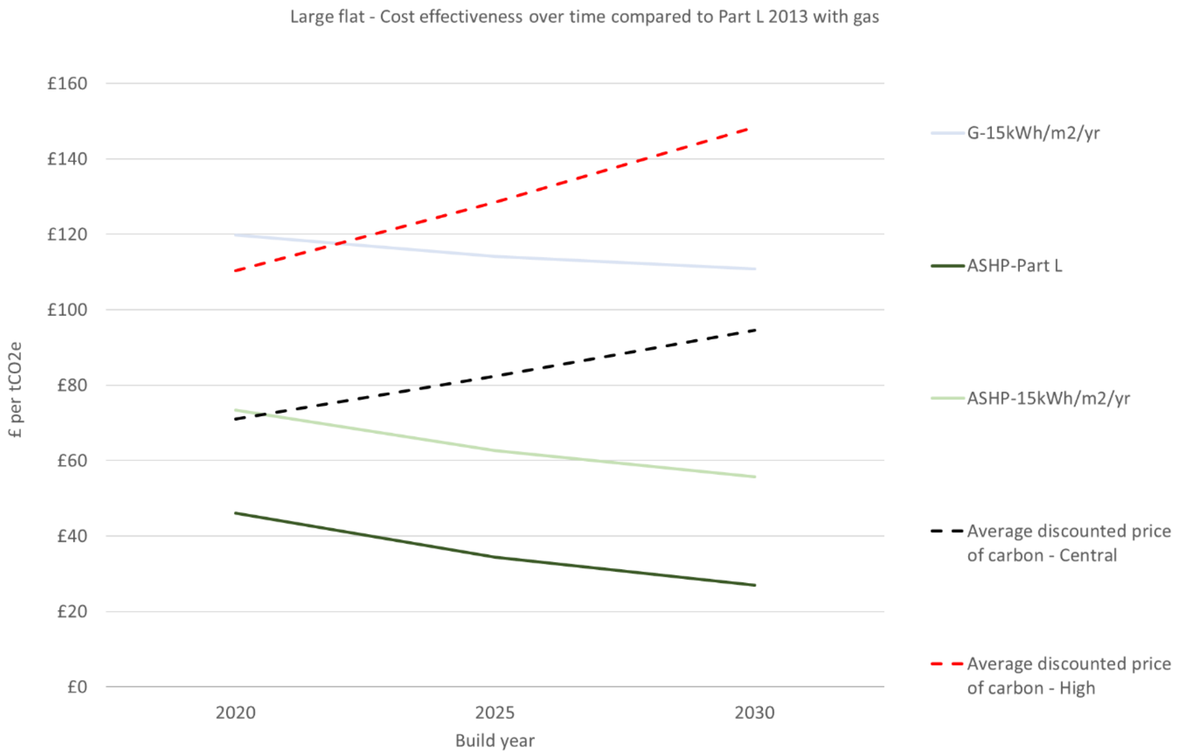
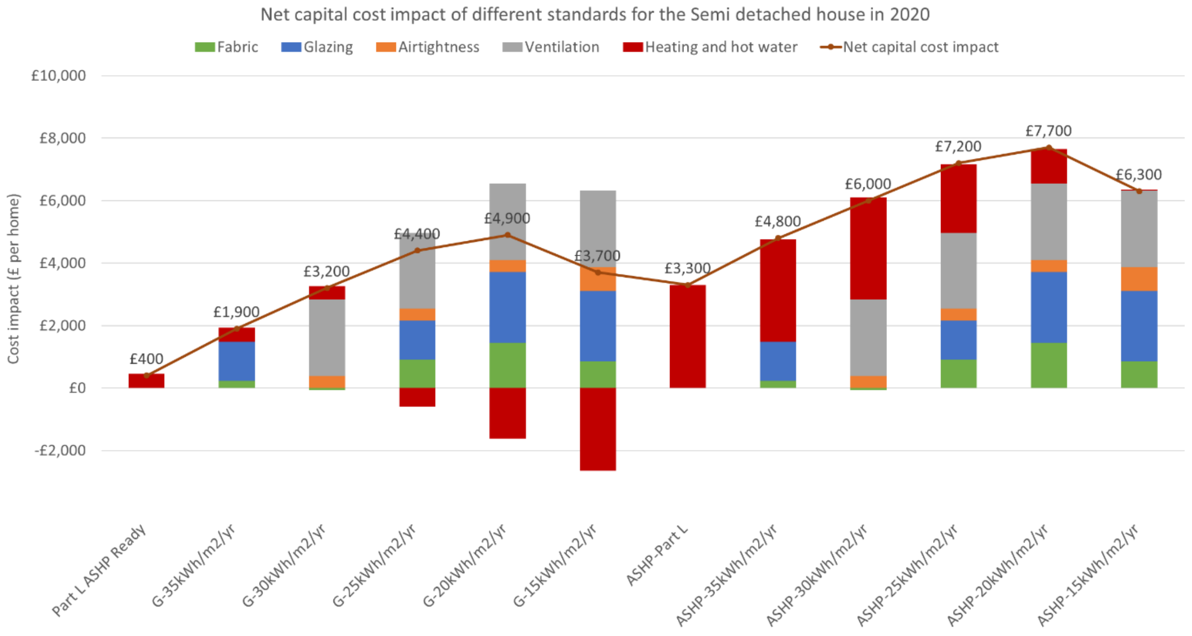


Figure F.9 Cost-effectiveness results for large flat – 2020-2030



Appendix G - Sensitivity analyses charts

Figure G.1 shows the results of the sensitivity analysis for high capital costs on the semi-detached house.



Figures G.2 to G.6 show the results of the range of other sensitivity analyses undertaken on the cost effectiveness results for the semi-detached house.

Figure G.2 Heat pump efficiency increased by 25%

Figure G.3 Construction costs at 132% of base prices

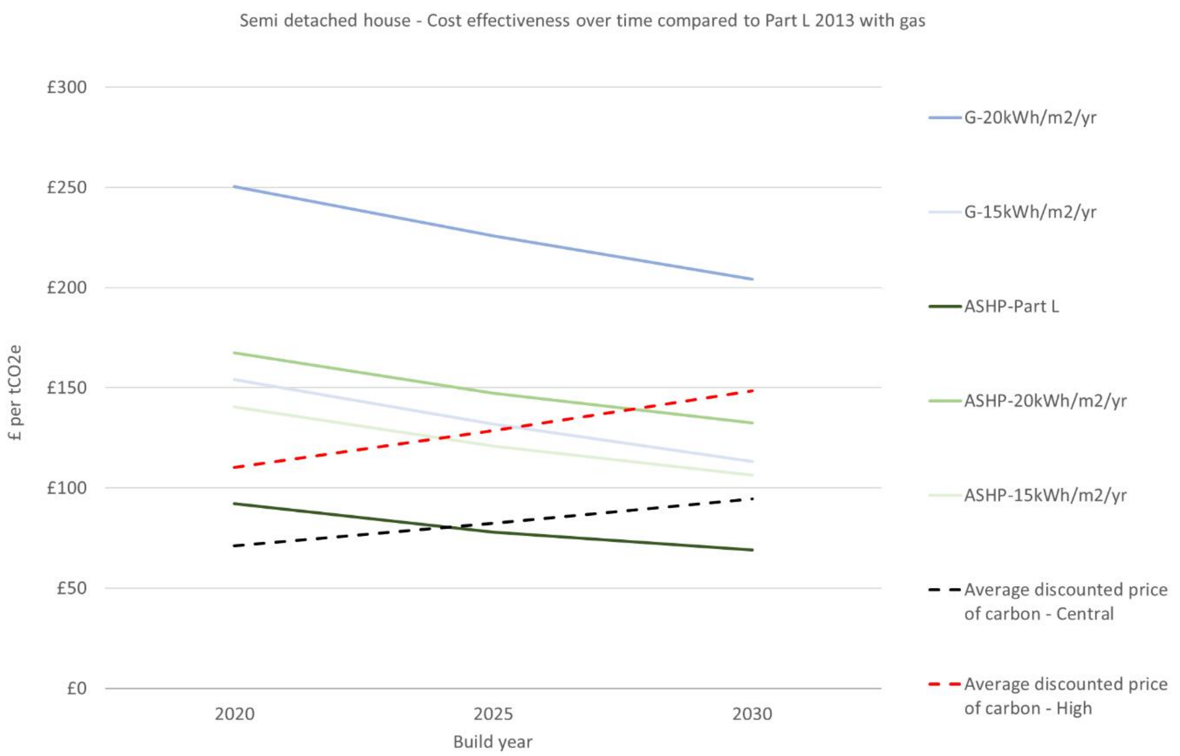


Figure G.4 Low LRVC of gas

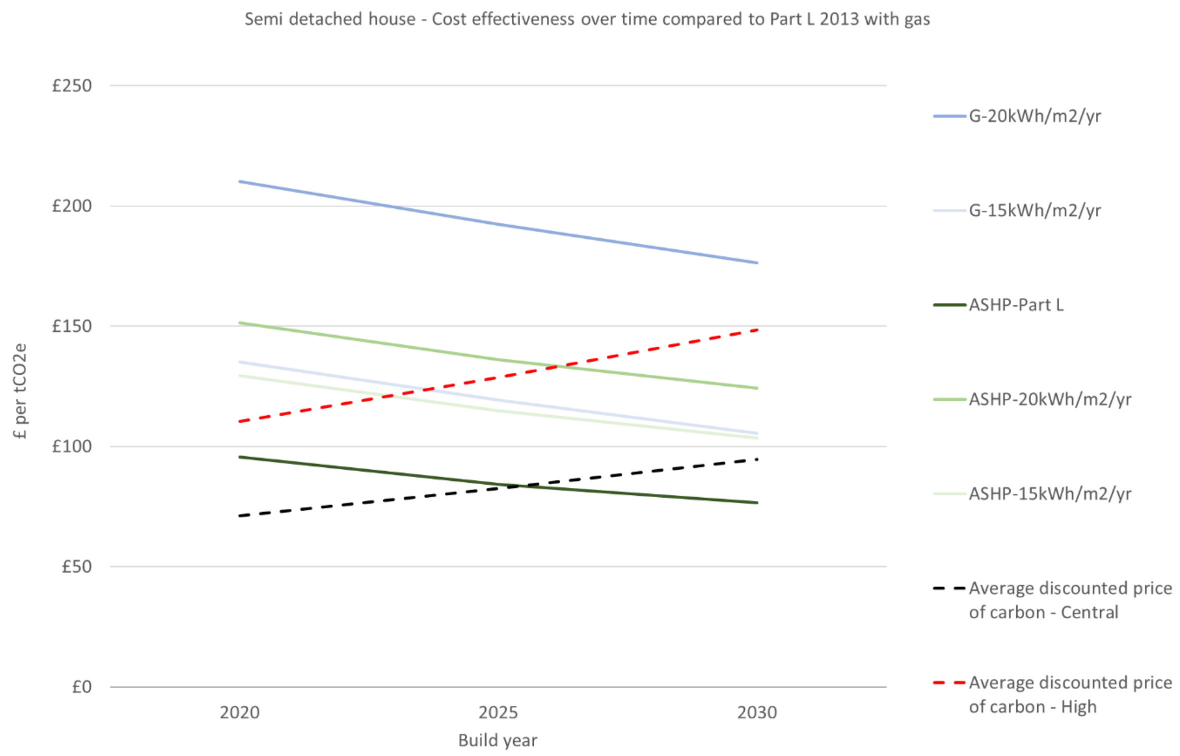


Figure G.5 High LRVC of gas

Figure G.6 Varying the scale of the reduction in heating distribution costs for ASHP-15kWh/m²/yr specification

Figures G.7 to G.9 show the results of the sensitivity analyses undertaken on the impact of changing the heat supply mix for the small flat with ASHP from a 70:30 mix between heat supplied by communal ASHP and gas boilers to a scenario with 100% of heat supply coming from an ASHP.

Figure G.7 Additional capital costs of reducing space heating demand in combination with different heating systems – small (high rise) flat in 2020 with 100% use of ASHP for heat

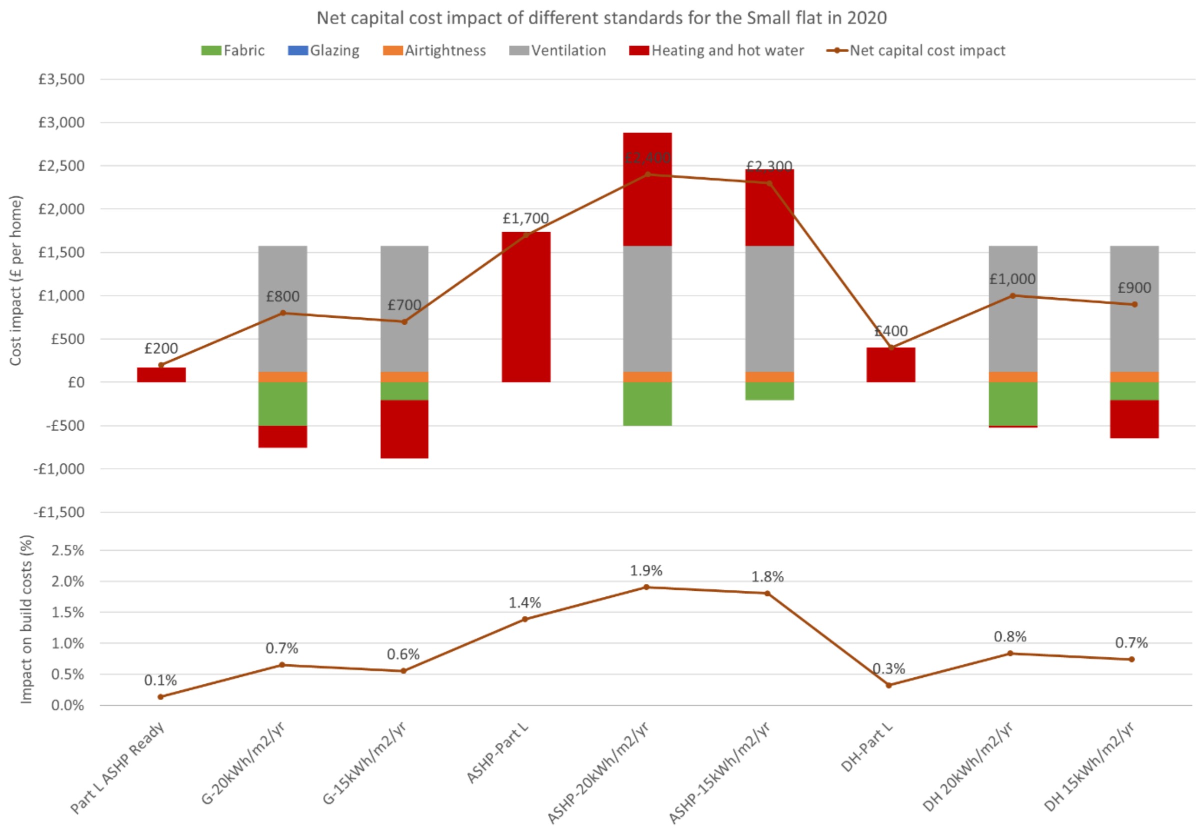


Figure G.8 Cost effectiveness over time for small flat house type with 100% use of ASHP for heat

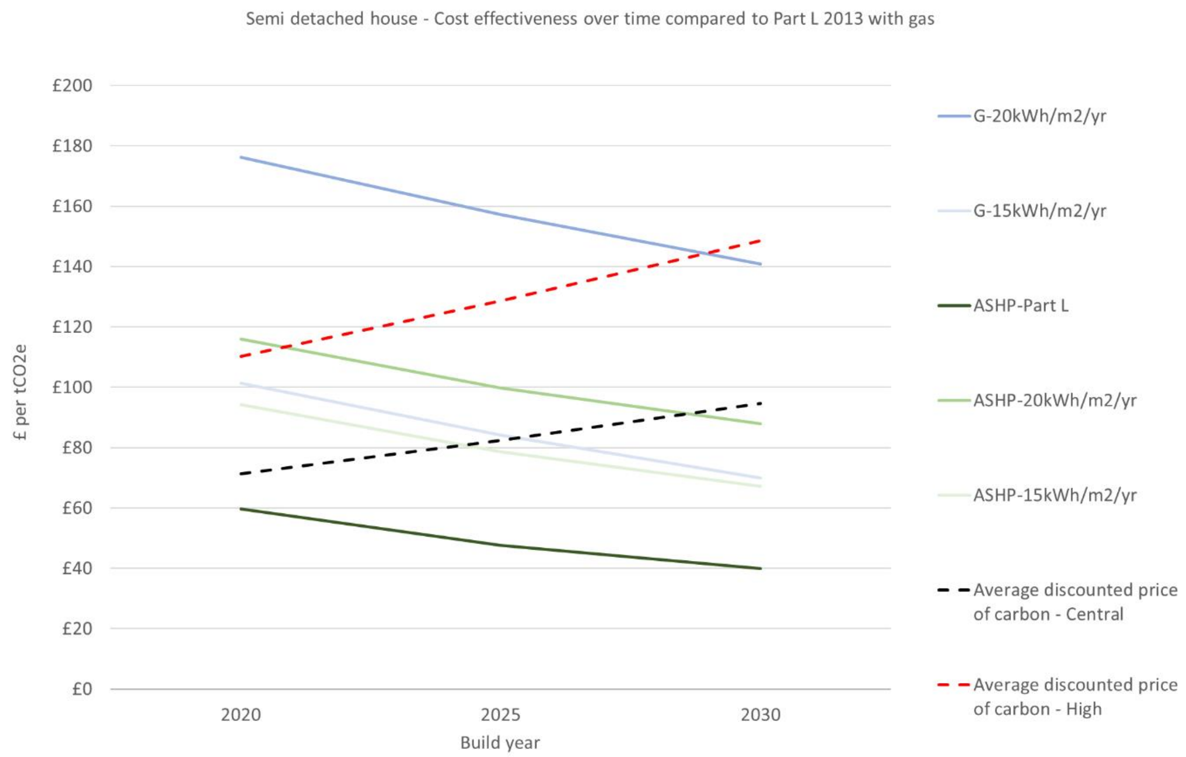
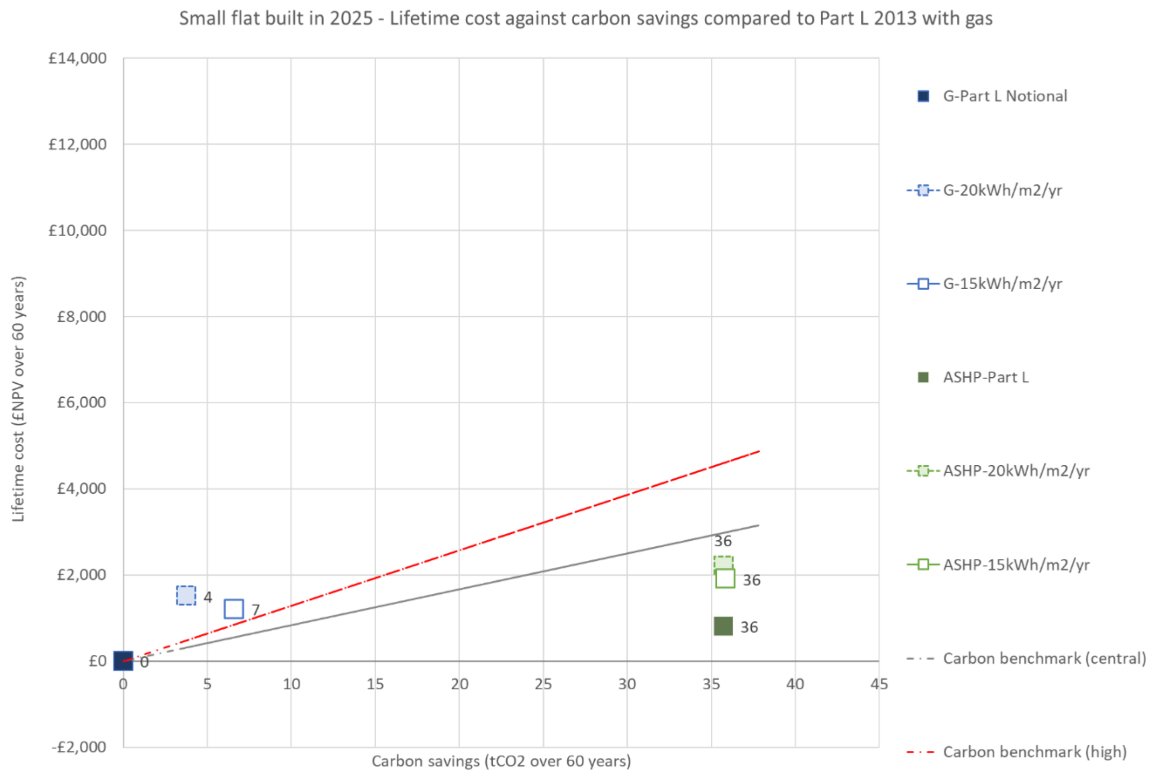


Figure G.9 Carbon savings and lifetime costs of small flat house type with 100% use of ASHP for heat in 2025



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