**Title Page**

**Title:** Appraising the Life Cycle Costs of Heating Alternatives for an AffordableLow Carbon Retirement Development

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# Abstract

This paper assesses the low carbon design of housing developments for retired people who are willing to downsize. There is a need for a strategic approach to provide energy-efficient housing in general, but specifically for a growing aged population. This approach should be inclusive and affordable. Therefore, this study assessed the capital and operational costs of space and water heating of typical UK retirement dwellings by considering, over a 30-year life cycle, the use, maintainability, replacement frequency, and sustainability of applying different low carbon energy technologies and renewables to various primary heating plants. Conventional heating systems (e.g. gas, electricity) and low carbon green technologies, such as photovoltaics (PV), solar hot water systems (SHW), combined heat and power (CHP) and air source heat pumps (ASHP), were studied and compared. A combination of ASHP and a solar hot water system (SHW) reduced the energy costs by 57%, maintenance costs by 14% and produced 46% lower carbon emissions than the gas boiler option. However, the ASHP option generated 75% more capital costs than the gas boiler scenarios as well as high replacement costs due to the short life expectancy of the system. The gas boiler and PV combination had the lowest capital, energy, and life cycle costs but also had high carbon emissions. The results suggest that UK government incentives, such as applying a carbon tax, would significantly reduce the payback time of green technologies and could, therefore, be the key drivers of low carbon adoption.

Highlights

* 4.5 times more energy is required for heat compared to regulated electricity.
* ASHP and SHW scenario had low energy, maintenance, and overall operational costs.
* ASHP and SHW had very low CO2e emissions but the highest capital costs.
* Heat incentives and applying carbon tax would reduce the payback time of renewables.
* Projection of future carbon intensity and cost of electricity is essential for life cycle analysis.

# Graphical Abstract

*The ranking of various scenarios against different criteria. Higher the ranking means higher the costs or emissions.* [*colour should be used for this figure in print]*

**Keywords:** Life Cycle Costing, Low Carbon Heat Technologies, Retirement Living, Affordable Housing

# Introduction

The use of energy in buildings to provide a comfortable and healthy indoor environment for occupants currently accounts for over 40% of the total primary energy consumption in the USA and the EU and causes substantial CO2 emissions [1, 2]. In the UK, direct greenhouse gas (GHG) emissions from buildings were 88MtCO2e in 2018, which accounted for 22% of the total UK GHG emissions [3].

Although heat generation is still the largest energy-consuming sector in the UK and the most significant contributor to UK GHG emissions, the overall demand for space heating in buildings is falling due to increasing fabric thermal efficiency. Despite a growth in the number of households in the UK, electricity and gas consumption for heating fell by 17% between 2005 and 2016. Several factors have contributed to these reductions in consumption, including energy efficiency improvements such as more energy-efficient appliances, new boilers and increased insulation levels, weather conditions, increased energy prices, the 2008 global recession, changes in the building stock and increases in solar photovoltaic self-generation by households [4]. However, gas, oil and coal are still the primary heating sources in Europe. In the UK, around 85% of households use natural gas for heat [5, 6]. This is incompatible with Europe’s commitment to climate change mitigation and the UK’s long-term decarbonisation goal. It is necessary to implement other low carbon heating options by the 2030s if the 2050 net-zero emissions target is to be met [7].

Developments in heat generation technology, heat delivery, and energy efficiency options now mean that there is an interest and an incentive for developers to install and use green and clean technologies within the Europe and UK building stock. However, most building developers still see investment in energy efficiency as a risk rather than an opportunity, and they avoid energy efficiency measures merely to reduce the risks involved and the potential reputational damage [8]. One of the sectors that could potentially benefit most from utilising clean and green heat technologies, but which has been comparably slow in adopting such an approach, is care homes and later living or retirement living homes [9]. Residents of these properties will frequently spend much of their time indoors, have low activity levels, and require very warm environments to provide comfort for much of the year.

Neven et al. [8] undertook a study of 27 care homeowners to assess their attitudes to implementing sustainable thermal technologies. The owner of a care home in Northern England, which used a solar hot water system (SHW), mentioned that implementing a low carbon heat technology might save £5000-£6000 in energy costs per year, equal to approximately £100 per resident per year, but that the risks of implementation might be higher than the savings. An owner of five care homes in Scotland with biomass boilers (and an oil-fired system as a backup) stated that they were unwilling to implement low carbon technology, even if the only risk would be a possible one-month delay in completion. However, all 27 participants in the study stated that government incentives, funding, and regulations would encourage them to implement sustainable technologies.

Other challenges that might be deemed as a risk when considering such technological shifts are necessary and perhaps radical changes to the lifestyle, behaviour and knowledge of the end-users and other stakeholders [10, 11]. As-built performance is another possible risk from implementing low carbon technologies. The importance of system performance increases with low carbon design. As with low carbon design, if a building’s heat losses are significantly higher than projected at the design stage, there will be a risk of the heating system being run at higher operating temperatures to try and meet the additional demand. This would result in significant increases in energy use [12].

Around 5,500 different care home providers in the UK operate more than 11,300 housing developments for the elderly, with about 410,000 residents. This sector is worth around £15.9 billion a year in the UK [13]. UK government funding was made available for producing long-term, affordable care and support specialised housing solutions in 2018 [8]. If new developers considered renewable energy generation and low carbon options then they could potentially access this funding and reduce operational energy costs in their developments. These new designs attract different types of tenure, management, and funding policies. Understanding the operational and life cycle costs (LCC) of different low carbon design options could encourage developers to consider these options, too, as they contribute significantly to the occupants’ health and wellbeing.

Buildings constructed for use as retirement (later living) homes or care homes have a relatively high and continuous demand for hot water, space heating and good ventilation. They could, potentially, hugely benefit from implementing low carbon heat technologies and might contribute meaningfully to the UK’s emission reduction target. A recent report on the carbon and energy costs of social care estimated a contribution of around 2.3 million tonnes of CO2 emissions and £468.5 million in utility costs [14].

Conversely, around 348,000 households aged 85 and over live in poor quality homes, and 92% of the total excess winter deaths (EWD), equal to 46,000 people in England and Wales during 2017 and 2018, were aged 65 or over [15]. Although two people of the same age might have distinctly different cognitive and physical capacities, and advanced age does not necessarily mean being vulnerable to cold, research suggests that poor health conditions can cause older people to be more vulnerable to the cold. Many older people are retired and on a low income, and so they may have trouble paying their energy bills [16, 17, 9]. Those in fuel poverty are underrepresented in discussions and policymaking, implying that a low carbon system will not necessarily improve access to affordable energy [18]. A household is considered to be fuel poor in England if:

* they live in a property with an energy efficiency rating of band D (the average value in England) or below and
* after paying the energy bills, they would be left with a residual income (equivalised income after housing costs, tax and National Insurance) of less than 60% of the national median [19].

Figure 1 shows that households using electricity as the primary fuel for heating have the highest likelihood of fuel poverty at 20.2%, compared to gas at 9.3% [20]. Despite these statistics, and although the UK’s ageing population is growing, around only 10% of Local Plans in the UK have a specific policy that addresses older people’s housing needs [21].

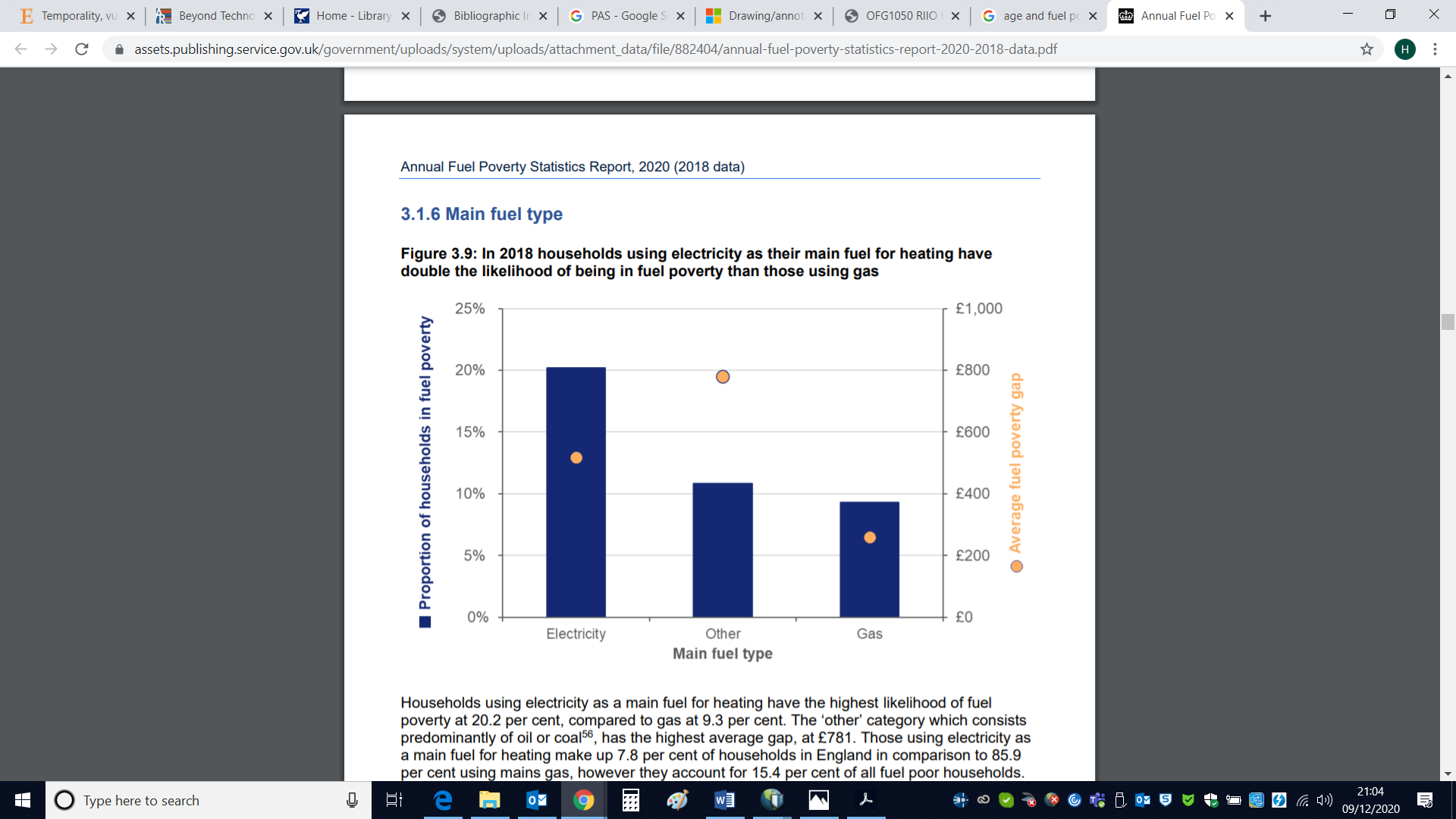


Figure – Shows that in 2018 households using electricity as their primary fuel for heating have double the likelihood of being in fuel poverty than those using gas. The ‘other' category consists predominantly of oil or coal [20]

Much research has been carried out on the suitability of various renewable and clean technologies and age-friendly spaces for retirement living developments [14, 18, 21], and negative impacts of low temperatures and fuel poverty on health [22, 23]. However, little research has been performed on comparing the life cycle costs of these various heat technologies. Existing studies [24, 25, 26] mainly focused on energy use and energy consumption costs whilst ignoring the life-cycle economic performance of these systems. A more holistic cost approach is required to make sure climate justice is considered in decision makings.

While the topics of integrated design, environmental performance, energy use, operational CO2 emissions, and life-cycle costs have each been examined, only a few studies [27, 28] combined all aspects together to determine the simultaneous impacts of energy-efficient design on life-cycle costs and carbon emissions in housing. As there is a need for a policy and a strategic approach to providing energy-efficient housing for the aged population, this paper aims to provide an overview of the affordable opportunities available and low carbon solutions for reducing carbon emissions from heat (heating, hot water) for a residential retirement living development (which included commercial spaces). This paper also reviews the distribution of costs involved in reaching low to zero emissions to allow policymakers to ensure that low carbon implementation funding and incentives are aligned with the required pace of change.

In addition, this research focus on the heating plant and clean and renewable technologies as they have the shortest lifespan of all building components and require continuous statutory and operational maintenance [29]. A life cycle option appraisal analysis conducted by Tokede et al.in 2016 [30] showed that replacing mechanical and electrical (M&E) plants had the highest cost of any refurbishment measure. Therefore, as well as technical appraisals, planning policies, and the carbon emission reduction potential of each technology, this paper have considered the broader consideration of these technologies' capital and life cycle costs.

# Aims and Methods

Low maintenance, low operational costs, and affordable living are often the main concerns that elderly people consider when selecting a retirement home [31]. Therefore, this research focuses on the life cycle cost assessments of various energy-efficient solutions that could be used in a proposed retirement living design (mainly for those who would be downsizing). To assess issues of fairness of future policies on heat electrification, this paper asks: does the emerging low-carbon technologies and heat electrification at the household scale complement or complicate minimising fuel poverty?

This paper highlights the capital costs of achieving the lowest energy costs for the occupants. The study 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 the cost-effective potential for tightening building regulations. More specifically, it assesses and compares three household heat technologies (gas, electric and the emerging technology of heat pumps) as the primary source of heat and three green and clean technologies (SHW, photovoltaic panels, and combined heat and power plant (CHP)) as the secondary energy plants.

A report from the University of Sheffield and the group Designing for Wellbeing in Environments for Later Living (DWELL) [32] has been used to select an appropriate design and case study. The report suggests several typologies for downsizer homes. In addition, it defines downsizers as general-needs housing and not age-exclusive or specialist retirement accommodation. Therefore, the result of this paper is not just limited to retirement accommodation – it also considers the aspirations and requirements of third-agers. Accordingly, a mid-rise, garden-block retirement living apartment typology with commercial spaces in the UK was selected as a case study to:

* identify the solutions that are most likely to produce the lowest energy bill costs for occupants, with the calculated energy costs to be comprised of both the energy consumed within the dwelling as well as the costs of energy consumed in the communal areas (but not commercial areas as this might vary from one project to another).
* help the financial sustainability and operational benefits derived from following the principles of the RICS professional guidance, UK Life cycle costing' [33] throughout the design development.

The generic site plan consisted of 77 residential units and approximately 2,300m2 of flexible communal floor area. An 85m2 top floor semi-detached apartment (chosen as the worst-case scenario due to heat loss through the roof) had been selected for the analysis. It was assumed that the apartments were separately metered, and the communal space utility, maintenance and replacement costs were shared between residents (as service charges). All the studies and cost analyses have been carried out at the design stage before the building was constructed. However, the energy and life cycle costs analysis data were provided by the stakeholders involved in the project (architect, building services engineers, manufacturers, and a quantity surveyor) and have been validated against the appropriate industry standards. Figure 2 illustrates a summary of this research’s steps and sources of data used for the analysis.

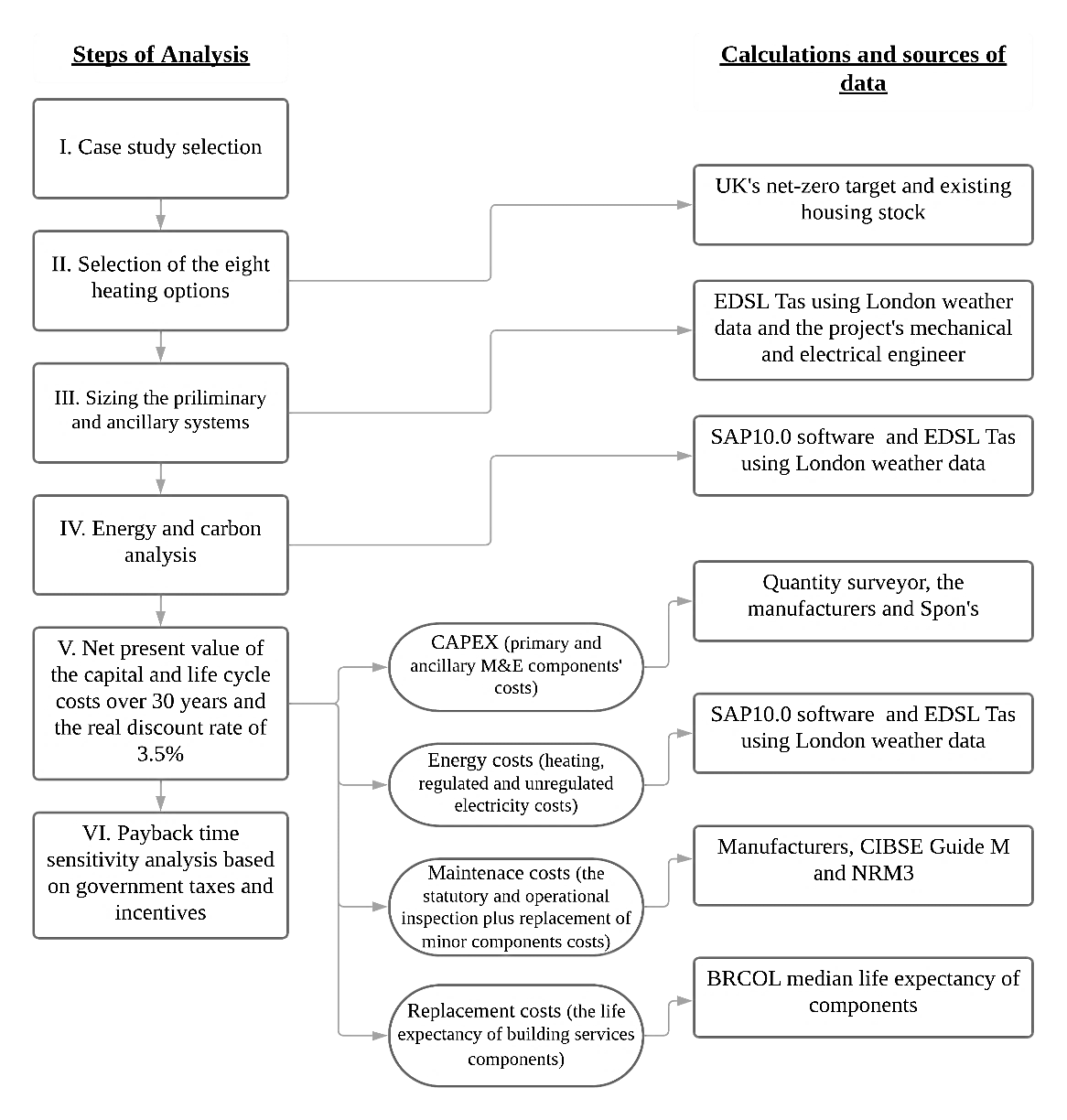


Figure 2 – Summary of the steps of analysis and methodology used in the study

## Selected scenarios for option appraisal

According to the DWELL project’s results [32], downsizers prefer locations within an easy walking distance of city centres, and the selected technologies are viable and low risk for the desired location of retirement housing [34]. The design followed the fabric first approach and the sizing of the technologies, and the heating plants were calculated based on the energy analysis results and validated by the project’s mechanical and electrical engineers and the manufacturers - see Section 2.2 for more details.

### Central gas boiler

The first primary heating option was to use a central gas boiler to provide heating and hot water to the apartments and communal spaces. Despite the UK Treasury's (HMT) announcement [35] on ending gas heating in new homes and the UK's 2080 net-zero target, fossil fuels continue to play a significant role in residential energy use, and there is still no guidance on how to meet the challenges involved in the HMT decision. There is also uncertainty regarding how much these changes could cost developers and end-users. In addition, approximately 85% of UK households and 65% of non-domestic buildings use natural gas for heating [4]. Gas boilers have been included in the scenarios not because they are considered low-carbon technology but to assess the cost-effectiveness of this predominant heating fuel, which has delayed implementing low-carbon technologies. Therefore, the combination of gas options and low or zero-carbon energy sources are included in the analysis to provide an opportunity to compare other options (e.g. electric and ASHP) against the gas boiler system. The assessments are based on three 300kW central gas boilers with an efficiency of 91%.

### Central electric hot water generation and local electric heating within the apartments

The second primary heating option was to use central electric hot water generation and local electric heating within the apartments. Particularly in premises that are off the gas grid, direct electric heating systems are the most common heating source, and it is becoming cleaner as the power sector continues to decarbonise. Since 2012, 75% of the reduction of the UK's greenhouse gas (GHG) emissions has come from the electric power sector [36]. This has resulted in a 55% reduction in the carbon emissions intensity factor for electricity, from 0.460kgCO2e/kWh to 0.233kgCO2e/kWh. This means that homes heated by direct electric systems will produce nearly the same carbon emissions as gas, with a 0.204kgCO2e/kWh conversion factor [37, 38, 39]. Any knowledge of the future cooling demand for the UK is currently limited, however. The UK's National Grid has previously estimated that the demand for air conditioners in the domestic sector will be 18 million units by 2050, compared to less than one million in 2018 [4]. Therefore, it is essential to study the cost implications of electric options for both developers and occupiers. Accordingly, a 250 litre hot water electric immersion tank was considered for the electric scenarios.

### Central air to water heat pumps

Central air to water heat pumps (ASHP) were the third selected primary heating option for this study. ASHP was selected due to site limitations and technical difficulties of applying ground source and air to air heat pumps. This scenario required hot water storage, which is considered in the capital costs estimations. Despite low market penetration in the UK, heat pump technology is essentially a mature and low-risk technology. Currently, one of the barriers to using ASHPs in the UK is the system's initial costs. However, with government incentives and low carbon plans, it is predicted that the cost of this technology can reduce by up to 20% in 2025 [40]. Another reason for selecting ASHP is the significant potential for retrofitting the technology to the existing housing stock. They can also operate in areas of high-density housing such as flats and terraced dwellings, where the installation of ground source heat pumps would be infeasible [34]. Accordingly, the assessments are based on 18x42kW central ASHPs with a coefficient of performance (CoP) of 2.98.

Solar-based renewable technologies

The ancillary options were selected based on the technical applicability and meeting policy and planning requirements. Dependent on the technologies used and the particular requirements, solar-based renewable technologies such as solar thermal hot water system (SHW) and Photovoltaic (PV) panels can be installed to deliver electricity, space heating, hot water and cooling. Therefore, for onsite renewable energy generation, in retirement living buildings, which are at the pivotal point of this study, SHW and PV panels are decidedly suitable options. The former can provide a thermal energy output for direct water or space heating, while the latter can provide electrical energy to cover partially a household’s electricity needs for regulated and unregulated electricity [41, 42]. The Standard Assessment Procedure (SAP) is a methodology used by the UKGovernment to assess and compare the energy and environmental performance of dwellings, and the SAP guideline was used to calculate the annual solar radiation levels over a12 month period. The same guideline was used to determine with south orientation and the 30o tilt angle for the SHW and PV panels [43]. Given the maximum roof space available, and to maximise renewable energy generation, 200kWth of SHW and 96kWth of PV panels were modelled for this study.

Gas-fired combined heat and power plant (CHP)

Like heat pumps, CHP can contribute to the decarbonisation pathways at the different scales of centralised, medium-scale and small-scale generation integrated in to each home through micro-CHP engines [44]. However, more recent literature suggests combining this technology with gas boiler and renewable technologies rather than as a stand-alone technology to meet low carbon targets [45]. Therefore, this technology has been assessed along with a gas boiler and PV panels. Calculations in this study are based on a 50kWth CHP. Table 1 outlines the eight scenarios that have been reviewed as part of the energy and life cycle costing option appraisal for the proposed scheme.

Table 1 – Selected heating technologies and low carbon and green scenarios

|  |  |  |
| --- | --- | --- |
| Scenarios | Primary Heating Plants | Supplementary Plant |
| Scenario 1 (S1) | Central Gas Boiler serving communal areas plus apartments | SHW |
| Scenario 2 (S2) | PV |
| Scenario 3 (S3) | CHP + PV |
| Scenario 4 (S4) | Electric Heating and Hot Water for communal areas and apartments | SHW |
| Scenario 5 (S5) | PV |
| Scenario 6 (S6) | Central Air to Water Heat Pump (ASHP) serving communal areas plus apartments | No Supplementary plant |
| Scenario 7 (S7) | SHW |
| Scenario 8 (S8) | PV |

Although a complete analysis of low carbon options would also include other heat options, such as biomass and ground source heat pump (GSHP), this paper does not aim to provide a complete answer to the heat decarbonisation problem. Instead, the overall aim here is to demonstrate the distribution of costs involved in reaching low to zero emissions through a case study research to allow policymakers to ensure that the low carbon implementation funding and incentives result in affordable low carbon buildings. Other researchers [46, 47, 48, 49] have taken the same approach when techno-economically assessing the low carbon technologies, rather than presenting a holistic review of all available technologies.

## Modelling and cost analysis

### Fabric first approach and thermal modelling

To follow low carbon principles [52], and to minimise the heating system size, this study first compared the energy consumption of an energy-efficient fabric design with one built to meet the minimum building regulation requirement. The analysis was run using the UK's Standard Assessment Procedure (SAP10.0) [50] software to measure the options against UK thermal building regulations (Part L1A) [51]. Accordingly, two thermal models were developed in SAP10.0 software using London weather data. First, a building model was configured to comply with the UK building thermal regulation Part L1A (Table 2) and to meet the Target Fabric Energy Efficiency (TFEE) rate [51]. This model did not meet the Target Carbon Emission Rate (TER) and, therefore, notional building specifications [51] were applied for the building fabric performance and airtightness. A fabric-first approach using Cross Laminated Timber (CLT) was then proposed in line with the best practice for low carbon design. The high-performance fabric provided added benefits in terms of airtightness and efficient construction.

Minimum compliance standards were assumed for the building service efficiency and ventilation for the Part L1A scenario. However, considering the importance and high ventilation demand in retirement living developments, mechanical ventilation with the rate of 30 m3/h or 8 l/s per person was modelled for all the compared scenarios. The proposed ventilation rate is recommended for highly low energy buildings (i.e. Passivhaus buildings) [53]. For all fabric scenarios, the residents can open the windows, which has been considered when sizing the heating system. All the services and the proposed scenarios in Table 1 were sized accordingly.

Table 2 – Comparison between the research case study (CLT compliant solution), the concurrent notional building specification, and the existing housing stock built to PartLA1.

|  |  |  |  |
| --- | --- | --- | --- |
| Building Elements | 2016 Building Regulations Part L1A requirement | Concurrent Notional building specification | Proposed Values using CLT construction |
| Roof (W/m2K) | 0.20 | 0.13 | 0.13 |
| Wall (W/m2K) | 0.30 | 0.18 | 0.15 |
| Floor (W/m2K) | 0.25 | 0.13 | 0.13 |
| Windows/ g-value (W/m2K) | 2.00 | 1.40 | 1.00 |
| Doors (W/m2K) | 2.00 | 1.00 | 1.00 |
| Air Tightness (m3/m2h@50Pa) | 10 | 5 | 3 (worse-case scenario) |
| Gas boiler efficiency | 89.5 | 91 | 91% |
| Ventilation | Natural ventilation with local extract in kitchen and wet rooms | Natural ventilation with local extract in kitchen and wet rooms | Whole house MVHR- Ventilation rate of 30 m3/h per person and efficiency of 75% |
| Annual heat consumption comparison (kWh) | 6900 | 5670 | 4610 |

To determine the average savings in heat costs for the occupants in the proposed scenario, the 2018 median national heat consumption for houses was also calculated. The heat demand of the CLT scenario (4610 kWh) was approximately 20% lower than the PartLA1 scenario (5670 kWh).

The National Energy Efficiency Data-Framework's (NEED) report of June 2020 [54], published by the UK Government’s Department for Business, Energy & Industrial Strategy (DBEIS), provided the mean energy use in domestic buildings. Comparing this data (6900 kWh) with the CLT scenario showed approximately 65% less heat (heating and hot water) costs.

The energy consumption generated from the SAP10.0 calculation for the apartments and the dynamic thermal simulation modelling (DSM) software EDSL Tas, were used for the communal areas, to estimate annual energy costs. London weather data were used for the analysis in both programmes.

### Life cycle cost analysis

To assess the life cycle operational costs and the carbon implications of the various design scenarios, the study reviewed the capital costs and the operational costs (cost in use) of applying various renewable and low carbon energy technologies to selected primary heating strategies over a 30-year life cycle period, which reflects the same period included within the operational model.

The life cycle cost analysis followed the Royal Institution of Chartered Surveyors (RICS) professional guidance, published in April 2016, [33] and the guiding principles outlined in the Building Cost Information Service/British Standards Institution (BCIS/BSI) publication PD15686-5 *Standardized Method of Life Cycle Costing for Construction Procurement* [55]. Accordingly, the varied costs of eight scenarios associated with (i) the capital costs of the core heating components combined with low carbon solutions, (ii) the estimated expenditure for utilities (heating, hot water, regulated and unregulated electricity), (iii) the maintenance costs, and (iv) the replacement costs have been analysed over 30 years.

Equation 1 shows that the Life Cycle Cost is defined as [56]:

|  |  |
| --- | --- |
|  | Equation 1 |

where:

LCC = life cycle cost (£),

IC = total initial cost (£),

∑= Sum over the lifetime, from year 1 to year N, where N = lifetime of the technology (years),

OCt = operating cost (£),

r = discount rate,

t = year for which operating cost is being determined

To estimate the discounted costs, the suggested real discount rate of 3.5% from HM Treasury's Green Book (2018) [57] for public sector projects has been considered. This rate is in line with inflation and does not need to be adjusted for inflation. The discounted costs are presented as the Net Present Value (NPV) of 30 years' worth of cashflow and compared with the gas boiler option with no ancillary plants.

For a project of this type, a quantity surveyor provided the expected capital costs, and various manufacturers provided the M&E specifications and maintenance requirements. The assumptions for each section of the analysis are included in the relevant result sections. Finally, a sensitivity analysis of the effect of government incentives and carbon tax on the payback time of scenarios were carried out and presented in the result section.

# Results and analysis

## 'Fabric-first' strategy

## Capital costs

After sizing each scenario's primary and ancillary heating components, the capital costs were estimated in collaboration with the project's quantity surveyor and validated using Spon's mechanical and electrical services price book [60]. Figure 3 demonstrates the estimated capital cost of simulated scenarios. Distribution, storage and emitter costs are all included in the capital costs.

Figure 3 – Capital costs of M&E installations for various heating strategies for the whole development (residential and communal areas)

As can be seen in Figure 3, ASHP incurs the highest capital costs among the preliminary heating plants and PV panels are the most expensive ancillary plant. A 2016 report from the UK government's Department of Energy and Climate Change (DECC) [40], predicted an overall cost reduction of 20% compared to the current costs for ASHP. However, sensitivity analysis by Rafique & Williams [49] showed that even after a 20% capital costs reduction for ASHP, a gas boiler would still incur lower capital costs.

The following sections of the paper present a summary of the corresponding operational and life cycle costs.

## Utility costs

To identify the low carbon solutions that are most likely to result in the smallest energy bills for occupants, the development's (apartments and communal areas) heating, regulated and unregulated electricity requirement, as well as the energy generation from the renewables and CHP system, were compared, and the utility costs were calculated and are presented in Figure 4. Utility costs of £0.045 and £0.155 per kWh were assumed for gas and electricity respectively. As similar assumptions were made for the occupiers' schedule and household electrical appliances, the regulated and unregulated electricity costs were the same for all scenarios. The regulated electricity was the electricity required for low energy LED lighting, mechanical ventilation and heat recovery (MVHR) systems, fans, and pumps. The unregulated energy consumption was the electricity required for small powered devices and typical household appliances and will be determined by the use and management of each apartment's occupants. The communal energy costs figure is what the apartment occupiers would pay to cover the communal spaces' energy costs (heat, regulated and unregulated electricity).

Figure 4 – The breakdown of the whole development's energy costs. The labels show the total energy costs, including income from RHI and FIT and the savings from renewables and CHP [colour should be used for this figure in print]

The UK government's Renewable Heat Incentive (RHI), and the Feed-in-Tariff (FIT) [61, 62] were included in calculating the total utility prices. ASHP is eligible for the RHI of 2.79 p/kWh of generation for 7 years and the PV panels generation is eligible for FIT of 1.73 p/kWh of generation for 20 years. The labels in Figure 4 show the total energy costs, including income from RHI and FIT. Non-domestic RHI rates are applied to the calculations because part of the generation might be used for communal and commercial areas in the future. The results show very low energy costs for scenario 7 (ASHP and SHW) compared to the other scenarios due to the ASHP's high CoP of 2.98 and ASHP's RHI payment (approximately £9805.53). However, as the FIT and RHI change every year, and to ensure that the decision-making risks are not increased, the energy costs were also compared, excluding the RHI/FIT income in Figure 5 for each apartment.

Figure 5 – comparison of an apartment (85m2) energy costs excluding RHI/FIT with associated M&E capital costs. The labels show the total annual energy costs, including the savings from renewables and CHP but excluding RHI/FIT [colour should be used for this figure in print]

Figure 5 also compares the capital expenditure (capex) as opposed to the occupants' energy costs to enable an informed decision on choosing the most affordable building design. The energy costs borne by each apartment would include utility costs for the energy consumed in the apartment plus the communal area energy costs, which would be divided between the 77 apartments.

Scenario 7 is favourable with and without RHI when comparing energy costs. However, it has the highest capital costs after scenario 8 (ASHP and PV). Gas solutions (scenarios 1, 2 and 3) have comparably low energy and capital costs. However, they have the disadvantage of requiring a gas supply to the site and for the flats to be very airtight. The best gas solution in terms of energy costs uses a CHP (scenario 3), but this is only recommended for larger-scale developments [63]. For instance, if the CHP is designed to provide part of the commercial area's energy requirements, that would be acceptable. The utility bills for the scenarios with electric primary plant (scenarios 4 and 5) are approximately three times more than the options with gas boiler (scenarios 1 to 3). The main reasons for this result are the higher heat demand and lower utility costs (0.045 p/kWh) for gas than electricity (0.155 p/kWh). Currently, the proportion of heat and regulated electricity demand for the whole development is 82 to 18 percent, but future cooling and ventilation demands may mean more electricity consumption, which would make the ASHP and electric scenarios (scenarios 4 to 8) more favourable.

## Carbon emissions

One of the research aims was to explore the operational carbon emission of alternative clean and green technologies. This paper considers all scenarios based on their operational carbon dioxide equivalent (CO2e) impact. The equivalent includes the other significant greenhouse gases that contribute to global warming potential [64]. The total CO2e emission of each scenario is presented in Figure 6. The labels show the total kgCO2e emissions per year for each option per apartment. The carbon intensity factors of 0.203kgCO2e/kWh for gas and 0.233kgCO2e/kWh for electricity were used to estimate and compare the carbon emission variation between the scenarios. The modelling software assumed a primary energy factor of 1.130 for main gas, 1.051 for CHP heat, and 1.501 for electricity [65].

In addition, London Planning Authorities (LPAs) apply carbon offsetting tax, following the London Housing Supplementary Planning (SPG) Guidance [66] on new developments. Currently, 15 out of 22 authorities rely on the price of carbon offsetting tax, as referenced in the SPG (£60 x 30 years = £1,800 per tonne of CO2e offset to be paid upfront). The remaining seven LPAs applying offset have adopted varying prices [67]. Therefore, the carbon offsetting tax that should be paid for each scenario is calculated using the SPG price and is presented in Figure 6. Scenarios 7 (ASHP and SHW) and 3 (Gas boiler and PV and CHP) with the lowest energy costs also have very low carbon emissions. Electric scenarios (S4 and S5) have both high energy costs and carbon emissions. Because currently, the carbon emissions intensity factor for electricity is higher than gas and the electricity costs are approximately four times higher than gas prices.

Figure 6 – Annual CO2e emissions and associated carbon tax (to be paid upfront) per apartment. The labels show the total annual CO2e in kg for each apartment, including the carbon emission reductions from renewables and CHP generation. [colour should be used for this figure in print]

## Life cycle costs

The relevant future energy, maintenance, and replacement costs of each scenario over the LCC period of 30 years were estimated to compare the options' capital expenditure with their operational expenditure (opex). The following sections are based on the best available data, mainly provided by the manufacturers. However, considering that good quality historical datasets are hard to find in the construction and real estate sectors [68], and that uncertainties are inherent in any forecasting method, these calculations are subject to change under different assumptions [69].

For all the calculated operational costs, the discounted costs are presented as the Net Present Value (NPV) of 30 years' worth of cashflow and compared with the gas boiler option with no ancillary plants. This comparison is presented in Figure 7, and as a percentage of saving (minus numbers) or as an extra cost (positive numbers).

Figure 7 – Predicted NPV of operational costs for each apartment and the proportion of the communal area per apartment for 30 years. Labels present a percentage of saving (minus number) or extra cost (positive number) compared with the conventional gas boiler.

### Life cycle Energy costs

The volatility of the annual price variation using historical electricity (2004–2018) and gas (2007–2019) prices was calculated to predict future fuel prices, and a binomial tree was constructed. Table 3 illustrates the predicted prices based on a 10.69% and 14.40% volatility rate for electricity and gas, respectively, at a five-year interval. Accordingly, 30 years of LCC energy costs were estimated and are presented for each apartment in Figure 7. When compared with the conventional gas boiler, electric scenarios (S4 and S5) incur higher energy costs. As mentioned before, the main reasons are higher heating and hot water demand and lower utility costs for gas. The highest energy cost saving occurs for Scenario 7 (ASHP and SHW) in which clean and green sources provide both heat and electricity, while for the scenarios with gas boiler primary plants (S1, S2 and S3), significantly higher costs savings are achieved when PV panels are installed as an ancillary plant (Scenarios 2 and 3) than SHW (Scenario1) because of the higher electricity costs than heat.

Table – Predicted future utility prices using binomial tree methodology

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Item | Year 0 | Year 5 | Year 10 | Year 15 | Year 20 | Year 25 | Year 30 |
| Electricity costs (p/kWh) | 15.48 | 15.88 | 16.30 | 16.72 | 17.16 | 17.60 | 18.06 |
| Gas costs (p/kWh) | 4.48 | 4.69 | 4.90 | 5.13 | 5.37 | 5.61 | 5.87 |

It should be noted that with government incentives for the scenarios with PV panels (S2, S3, S5, S8), they will also benefit from fixed electricity tariffs for 20 years. This parameter is considered when calculating the payback time of scenarios in Section 3.6.

### Life cycle maintenance costs

Information on maintenance requirements was obtained from the Royal Institute of Chartered Surveyors (RICS), New Rules of Measurement 3 (NRM3) [70] and the Chartered Institution of Building Services Engineers (CIBSE) Guide M [71]. The maintenance costs that are included in this analysis, which were obtained from various manufacturers, are:

* statutory and operational inspection costs suggested by the CIBSE Guide M and NRM3
* replacement of minor components advised by the manufacturers
* cleaning as suggested by the manufacturers (the CIBSE Guide M and NRM3)

The life cycle maintenance operational costs would be paid as service charges by the future apartment occupants. It should be noted that the repair costs that may be required over the assumed 30-year analysis period have not been included in any systems. As seen in Figure 7*,* the maintenance costs of the electric scenarios (S4 and S5) are higher than those of the gas boiler (S1, S2 and S3) and ASHP (S6, S7 and S8).

According to NRM3, annual operational inspections are required for radiators, which are included in the electric scenarios (S4 and S5). This operational inspection would cost the occupants an NPV of approximately £3674 for all the apartments over a 30-year period.

Figure – Net Present Value of maintenance cost of M&E components over 30 years compared with the capital cost of each component for the whole development (the costs might vary for different options]

Considering that the capital costs of this component would be approximately £200 per radiator (5 radiators per apartment) with a life expectancy of 20 years, the occupants may not choose to comply with this non-statutory requirement. Figure 8, accordingly, compares the 30-year NPV of maintenance costs of different M&E components against the capital costs for the whole development. It can be seen from Figure 7 that, despite a high capex, the low carbon and green technologies have low maintenance costs, with ASHP scenarios (S6, S7 and S8) having lower maintenance costs than all the gas boiler scenarios (S1, S2 and S3).

### Life cycle replacement costs

Incorporating the building component's life expectancy was necessary for the life cycle economic appraisal of a building. Attention to the life expectancy of building services components in life cycle option appraisal is essential as they have a shorter life expectancy when compared to other building components. The Building Cost Information Service (BCIS) has carried out a survey of the experience of building surveyors to establish the typical range of life expectancies for building components. The survey findings, which were published and available in the Component Life module of the BCIS Building Running Costs Online (BRCOL) [72], were used for this analysis. Among M&E components, gas boilers, CHP, SHW, PV, electric heating tanks, and heat emitters have the most extended median life expectancy of 20 years, while ASHP, the MVHR units and the pumps have a shorter median life expectancy of 15 years.

Replacement costs were estimated using the NPV of the original capital costs estimate, an industry-standard approach, and are presented in Figure 7. It can be seen that ASHP scenarios (S6, S7 and S8), with the highest capex and short life expectancy, have the highest replacement costs.

## Total life cycle costs

A comparison of the capital costs and the NPV of operational costs for eight scenarios (over 30 years) is summarised in Figure 9, which ranks each scenario against different cost variances. The labels show the percentage of each cost over 30 years compared to its total LCC (capex and opex). It also shows the amount of emissions reduction from each scenario compared to the gas boiler with no ancillary plant. Scenario 2 (gas boilers with PV) has the lowest operational costs and low capital costs. PV panels work well financially in carbon emission reduction when combined with the gas boiler. This strategy is simple to operate, has a reasonably long life expectancy, and lowers life cycle operational costs. For the scenarios with ASHP as the primary plant, and electric scenarios, SHW (S7 and S4) incurs lower LCC, lower opex and higher CO2e emissions reductions than the PV scenarios (S8 and S5). Compared to scenario 1, the combination of ASHP and SHW (scenario 7) incurs a 51% higher capex, resulting in a 74% more CO2e emission reduction and could reduce the opex by 3.7%. Therefore, Scenario 7 would be an affordable low carbon design solution to replace the gas boiler for the proposed retirement living development. However, more research and development to improve the efficiency and service life of these technologies are necessary. For the electric primary heating plants (S4 and S5), scenario 4 with SHW have a lower LCC than the PV scenarios (S5 and S8).

Figure 9– Comparison of the net present value of life cycle costs over 30 years for the whole development. [colour should be used for this figure in print]

In addition, and assuming the continuance of heat electrification, the electric scenarios (S4 and S5) are simple to apply and are developers' first choice for apartments and flats. Though, it can be seen from Figure 9 that the operational costs contribute significantly (60-70%) to the total LCC (capex and opex) of the electric scenarios mainly due to high utility costs.

## Payback time sensitivity analysis

Comparing the NPV of the cash flow in all eight scenarios with the gas boiler option (with no clean or green supplementary plant) showed that only two scenarios would have a payback time of less than 30 years among the eight studied scenarios. Scenarios 2 and 3 would have payback times of 13 years and 19 years, respectively. Inclusion of government incentives (e.g. RHI & FIT) would reduce the payback times to 11 and 16 years for scenario 2 (gas boiler with PV) and scenario 3 (the gas boiler with PV and CHP), respectively. The carbon tax is another factor determining payback times, with the payback time of scenario 1 reducing from more than 30 years to 14 years. Table 4compares the payback time of scenarios with the gas boiler plant with no ancillary plants.

*Table 4* – *payback time of gas boiler scenarios compared to the gas boiler with no low-carbon supplementary plant option*

|  |  |  |  |
| --- | --- | --- | --- |
| Options | S1 | S2 | S3 |
| Payback time excluding RHI/FIT and carbon tax (years) | More than 30 years | 13 | 19 |
| Payback time including non-domestic RHI/FIT only (years) | More than 30 years | 11 | 16 |
| Payback time including carbon tax only (years) | 14 | 6 | 7 |
| Payback time including RHI/FIT and carbon tax (years) | 14 | 5 | 6 |

# Discussion and conclusion

Worldwide, the number of people aged 60 and over is estimated to grow by 56% (from 901 million to 1.4 billion) between 2015 and 2030, reaching 2.1 billion by 2050 [31, 73]. Many aged householders live in homes that are inadequate for their needs. In England and Wales, there has been an increasing number of excess winter deaths during recent years, while only around 10% of local planning authorities have a specific policy that addresses older people's housing needs. Many countries currently face the same challenge of planning for the housing requirements of an ageing population [74]. Mulliner et al. [31] have reviewed the existing literature on the set of housing and environment characteristics linked to older people's health and wellbeing and concluded that warm and dry are the primary preferences and requirements of the aged housing. There is a clear need for a policy and a strategic approach that provides low carbon housing, in general, but specifically for the aged population worldwide. This approach, however, must be inclusive and affordable.

Therefore, this research covered the capital and operational costs of the most commonly used low carbon and green heat technologies at the household scale, using a residential retirement living development as a case study in the UK, an example of an industrialised country with a zero carbon target. The aim was to assist developers and policymakers in making an informed decision on the optimum design of clean and green energy solution configurations and incentives or funding to meet the net-zero emissions target in this sector while providing good quality, affordable housing.

All the scenarios were assessed and sized against a reasonable quality building fabric baseline to follow the fabric-first approach, which led to a very low energy requirement. In addition to the energy efficiency and carbon reduction benefits, this approach would reduce the size of heating services in the building and make the buildings cheaper and easier to run. Comparison of the eight low carbon scenarios with the gas boiler with no supplementary heating plant demonstrated the highest energy costs savings of 57% and 50% for the ‘ASHP and SHW’ and the ‘gas boiler, CHP and PV’ scenarios, respectively. The same percentage of energy cost saving of 40% occurred for the ‘gas boiler and PV’ and ‘ASHP and PV’ scenarios. Among the clean and green technologies assessed in this study (SHW, PV, CHP and ASHP), the SHW system had the lowest maintenance and replacement costs. As mentioned before, ASHP scenarios incurred the highest capital costs. Assuming an overall cost reduction of 20% compared to the current costs for ASHP [37], the replacement costs of these scenarios would also reduce and, considering low energy and maintenance costs, ASHPs would be attractive options in the near future.

**4.1 Carbon intensity factor**

However, they have high carbon emissions. The CO2e emission of the 'gas boiler and SHW' scenario was approximately 12% – 27% higher than the CO2e emission of the 'ASHP and PV' and 'ASHP and SHW' scenarios. This gap is predicted to widen as the net carbon savings associated with electricity generation will decline as the grid decarbonises while the emissions associated with gas use are not projected to change. According to the International Energy Agency (IEA) 2019 report [75], electricity generation from renewable sources increased by over 7% in 2018 worldwide, injecting an additional 450 TWh into global electricity networks. Increasing output from nuclear contributed another 90 TWh of low-carbon generation. Therefore, estimating accurate CO2e emissions of the ASHP and electric options compared to onsite generation and gas options requires further information on the carbon intensity of electricity. While the emissions intensity of electricity declined for Germany, Japan, Mexico, France and the United Kingdom due to nuclear and renewable generation sources, countries like China, India, and the United States produced more electricity using gas and coal [75]. This projection is currently not included in software packages used to meet the target carbon emission rate of building regulation. Considering the life of a building and changes to the electricity carbon intensity factor, this can be considered as one of this study's limitations.

## **4.2 Costs – Government incentives and carbon tax policies**

The authors found that with the current trend for the uptake of low carbon technologies, and in the absence of any government intervention, gas boilers continue to be the most affordable heating system, followed by PV, providing the most significant emission reduction. This is in line with other studies’ findings, such as Rafique & Williams [49] and Lowes, et al., [76].

Including London's current carbon offsetting policy, the 'gas boiler and SHW' option (with lowest capex) will have approximately £50k more carbon tax than the ASHP and SHW (with lowest carbon emissions and energy costs). By comparing the payback time of the gas boiler scenarios, including clean and green technologies, to the 'gas boiler with no low-carbon supplementary plant' option, the significant effect of government incentives and carbon tax policies on the payback time of low carbon technologies could be seen. The payback time of adding PV panels was reduced from thirteen years to five years when these two factors were included in the cashflows. Although a cost on carbon results in a greater adjusted internal rate of return on low carbon investments, and makes low carbon projects more attractive relative to alternative investments, it also risks creating new problems for households if it is conducted without considering the unintended consequences of the transformation [10, 77]. For example, some households without access to low carbon energy networks may be harmed by carbon taxes, or the extra costs of carbon tax might be sought from future buyers or residents. Kozarcanin, et al. [78] suggest using gas heating as a bridging technology to low carbon heating technologies, for example, through hybrid heat pumps. In addition, the inclusion of government incentives (e.g. RHI & FIT) would reduce the payback times to 11 and 16 years for scenario 2 (gas boiler with PV) and scenario 3 (the gas boiler with PV and CHP), respectively. Such incentives play an important role in increasing public involvement in installing low-carbon technologies. The experience with PV in the UK shows that the effect of government incentives in small scale installation numbers are more significant than the capital cost reduction. Although the average cost per kW of a small-scale solar PV reduced by 13% between 2013 and 2018, the installation numbers only increased when the FIT accepted applicants [49].

## **4.3 Fabric efficiency and energy demand**

The results suggest that there is 4.5 times more energy requirement for heat compared to the regulated electricity, but this might change with future electricity demands for ventilation and cooling. The UK’s National Grid has previously estimated that the demand for air conditioners in the domestic sector will be 18 times more than current figures [4]. Because of overheating concerns, planning for future cooling and ventilation demands is vital for designing retirement living developments. The ASHP scenarios, which provided electricity with 300% efficiency, or a hybrid solution of a gas boiler and ASHP, would be compelling options. In addition, as can be concluded from this study, the operational costs of heating and low carbon technologies are quite high. This is mainly due to maintenance requirements and the short life expectancy of M&E services. Therefore, the most cost-effective option would be a more airtight and energy-efficient fabric that could reduce the size of the technology in the building, which would also result in lower operational costs. However, more fabric- efficient homes mean that, proportionately, more energy will be required for hot water than heating. Therefore, sensitivity analysis is required to compare the lifetime carbon savings achievable from the use of low-carbon heat compared to the most energy-efficient fabric standards, which is another limitation of the presented results in this paper and which will be considered in future research.

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