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Relight my fire? Investigating the true cost of

April 2023

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Global Action Plan

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At Impact on Urban Health, we want to change this. We believe that we can remove obstacles to good health by making urban areas healthier places for everyone to live. Our ten-year Health Effects of Air Pollution programme is designed to find equitable solutions for poor air quality in cities. We work with a range of organisations, including government, industry and the communities that are most affected by air pollution, ensuring any interventions and solutions work for them.

Executive Summary

This report investigates the cost implications of the use of woodburning stoves, in a contemporary UK residential setting. The report compares a range of wood burner options against different heating systems, behavioural and occupancy assumptions. This study aimed to investigate the relative cost of wood burners vs alternatives in the context of the current and future energy prices. To achieve this, we undertook simulation modelling of a typical 3-bedroom London mid-terraced house (double glazed, with loft insulation), with two occupancy scenarios:

Scenario 1: a higher occupancy scenario based on a family of four, and
Scenario 2: a lower occupancy scenario based on a retired couple with no children at home, where some rooms were unheated.

Our simulation models were based on five heating system options (A-E):

A. Existing gas boiler providing 100% of heat
B. Newly[1] installed Defra-compliant woodburning stove led heating (80%) with gas secondary heating (20%)
C. Existing gas boiler (80%) with newly installed Defra-compliant wood burner secondary heating (20%)
D. Existing gas boiler (80%) with existing wood burner secondary heating (20%)
E. Newly installed Air Source Heat Pump (ASHP) providing 100% of heat

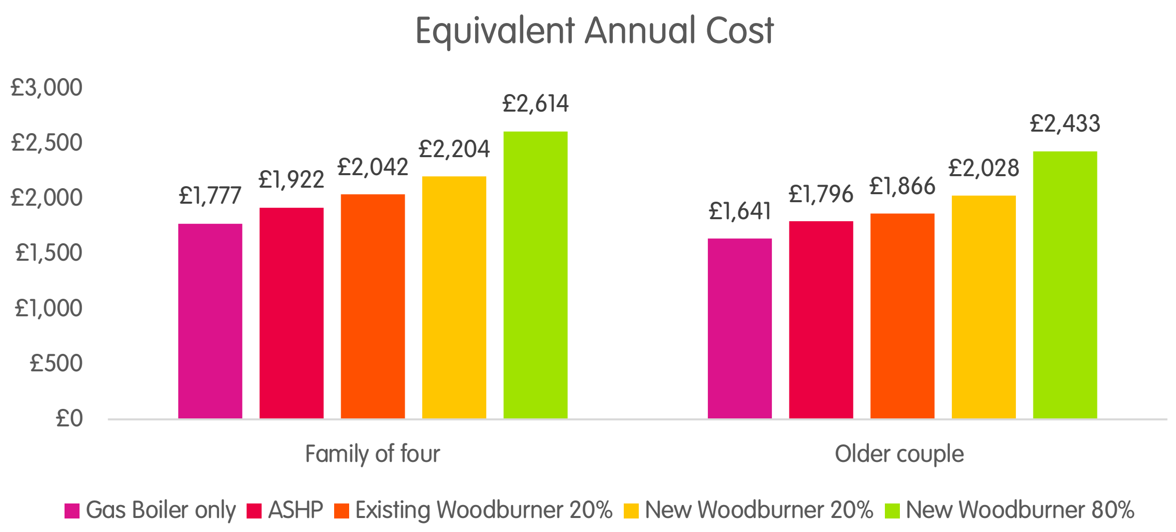
Using an in-depth literature review we then examined the economic, environmental and health impacts of these scenarios, including a sensitivity analysis of major sources of variability in these inputs. This produced 5 core findings:

Finding 1: We find little evidence that wood burners are a cheaper option, and in most cases are likely to be more expensive than the alternatives.

Our modelling suggests the total cost of wood burners is likely to be more than a gas boiler or an ASHP, in most cases. In our central scenarios, the high wood burner adoption, Option B, had an annual cost of ownership[2] of between £2,614-£2,433, 47%-48% more than using an existing gas boiler (Option A) at £1,777-£1,641. The lower use wood burner scenario (Option C) had annual ownership costs of £2,204- £2,028, or 24% more than the gas boiler. Even where the wood burner was existing (Option D), annual ownership costs were £2,042-£1,866, still 15%-14% higher. The ASHP (Option E) had

[1] "New" includes the cost of purchasing the item and installation, while all options include maintenance and replacement costs
[2] The equivalent annual cost (EAC) is the discounted annual cost of owning, operating, and maintaining the asset over a 15-year life

annual costs of £1,922-£1,796, 8%-9% higher than the gas boiler. These are summarised in the figure below.



Finding 2: Only where a large majority of the wood fuel can be provided for free, are wood burners likely save households money.

UK wood fuel prices have increased 44.3% in the last 5 years, partly driven by increasing demand. We found very large variability in the purchase price for wood logs, depending on the source. In general wood purchased in bulk, online, was significantly cheaper than wood bought in small quantities from non-specialist suppliers. Our research suggests that recent claims that wood burners are cheaper than natural gas heating, are based on £/kWh estimates at the very low end of this price range and are therefore highly optimistic. Moreover, unless wood is purchased in bulk from specialist suppliers, these costs may be substantially higher, with some sources of wood fuel (i.e., from garages) almost four times more expensive than gas.

Finding 3: The health impacts and associated costs of wood burning stoves are very significant, although again subject to large ranges.

We found wood burners are likely to create very significant health impacts. Long-term exposure to air pollution contributes to chronic conditions, e.g., cardiovascular, and respiratory diseases and lung cancer. Short-term exposure to high levels of air pollution is typically associated with acute health outcomes, such as exacerbation of asthma, increases in respiratory and cardiovascular hospital admissions and mortality. The type of wood stove used is hugely important especially regarding particulate emissions (PM 2.5, PM10). Well dried wood, burned in an eco-stove produces two orders of magnitude less air pollution than wet wood burned in an older stove. In our high wood burner adoption scenario (Option B), these public health costs were £9,060 (Scenario 1) and £8,171 (Scenario 2) over a 15-year period. If we assume the worst-case use of damp wood in an older stove (Option D) these costs rise to £39,243 (Scenario 1) and £39,106 (Scenario 2) respectively.

Finding 4: The environmental impact of wood fuel is uncertain and is dependent on sustainably managed forestry. Heat pumps are likely to be a much greener option in the long term.

While lower carbon than gas boilers, wood fuel cannot be considered to be carbon neutral. We found a 69% reduction in carbon costs vs a gas boiler in the high wood burner adoption Option B, although our modelling shows that ASHPs are likely to have the lowest carbon costs (90% less than gas boilers). However, biomass's climate change impact depends on the time frame being studied, the type of biomass, combustion technology, and what forest management techniques are employed in the areas where the biomass is harvested.

Finding 5: When factoring lifetime economic, environmental and health impact costs ASHPs are significantly lower cost than gas boilers, with wood burner significantly higher cost.

In our central scenario, we found the total cost impact of wood burners to be substantially higher than either the gas boiler or ASHP. With the high adoption Option B costing 42%-43% more than a gas boiler, the lower use Option C being 19% more, or 30%-33% more if the wood burner was an older model (Option D), despite the installation savings. By contrast we found that when factoring economic, environmental and health impact costs, the ASHP was only 79%-80% of the total cost of the gas boiler over its 15-year life.
We therefore find little evidence that wood burners are a cheaper option, and in most cases are likely to be more expensive than the alternatives, especially when factoring in health and environmental costs. However, the chosen input assumptions are critical in determining the overall cost impact.

Introduction

Wood is often referred as a clean and green energy source given its classification as being "renewable" (Directive 2009/28/EC). Indeed, use of wood burners has been increasing in developed countries over the last decades. UK Industry data indicate that annual stove sales are between 150,000 and 200,000 units with over one million stoves sold between in 2010 and 2015 (Font & Fuller, 2017). Soaring energy prices this winter have sparked even greater interest in using wood burners to provide what is perceived as cheaper space heating, with evidence of a 40% increase in market share since the energy price crisis[3]. However, the warm glow of a domestic fire might come at high health, air pollution and carbon costs whilst not even delivering monetary savings. This report investigates the cost implications of the use of wood burning stoves, in a contemporary UK residential setting. The report compares a range of wood burner options against a range of different heating systems, behavioural and occupancy assumptions. This analysis includes the cost of different fuel sources, the capital costs of installing different heating systems and the operational cost of maintaining them. In addition, we quantify the environmental costs of these different systems, by evaluating the social cost of the associated greenhouse gas emissions. Finally, we investigate the damage costs implications of a range of environmental pollutants which result in particular from increased mortality from small particulate matter (PM) exposure. This aim was therefore to investigate the true cost of wood burners vs alternatives in the context of the current and future energy prices.

The report is structured as follows. Section 2 briefly reviews contemporary academic and grey literature on the economic, environmental health and social impacts of wood burning for space heating. Section 3 outlines modelling approach, details of the ten modelled scenarios and the energy demand profile of a 3-bedroom reference dwelling. Section 4 outlines the economic, environmental health and social impact assumptions which inform our cost modelling. Section 5 presents the results of the cost benefit analysis including economic, environmental and health costs. Section 6 provides conclusions and policy recommendations.

[3] https://inews.co.uk/news/gas-price-hike-woodburners-winter-heating-buylogs-stoves-chimney-sweeps-1244646

Literature review: the economic, environmental, health and social impacts of wood burners

Broadly, wood fuel in the UK falls into three main categories. Highly processed and compressed wood pellets, less processed wood chips, and finally wood logs - the least processed and standardised category. This study is focussed on the economics of wood burners burning logs and therefore does not include further discussion of pellets or chips. There is further significant diversity within wood logs as a fuel, with different species of hard and softwoods having different combustion characteristics, and different levels of treatment, with kiln dried logs typically having a moisture content of >20%, naturally seasoned logs around 25%, while fresh cut logs may contain above 50% moisture. In general, the higher the moisture content, the less efficiently the log will burn, meaning less heat and more air pollution. What follows is a brief literature review adopting a snowball approach in Scopus and Google Scholar, searching for a variation of keywords for "wood burner", "wood fuel", "biomass" and their "economic" "climate" and "health" impacts, but with no specific document search strategy.

2.1 Economics

Unlike most primary energy inputs, the costs of wood fuel are highly uncertain. Commodities like oil coal and natural gas (and to a lesser extent coal) are traded on international markets, with daily published reference prices using comparable units, extensive historical records, and future projections readily available. By contrast wood fuel prices are highly subject to local factors and dependent on the scale, transportation and storage methods adopted. While there are no standard reference values for the cost of wood logs, there are several sources which provide estimates. The Forest Research agency of the Forestry Commission is Great Britain's principal forestry research organisation. The Forest Research "Small Roundwood Price Index" - including chipwood, pulpwood and woodfuel –was 12.9% higher in real terms in the 6 months to September 2022, compared with the previous year, against a backdrop of a 44.3% increase in the last 5 years, with current prices of £44.51 per m3[4]. Indeed, various industry sources[5] describe a 30 - 50% price increase for kiln dried logs, when compared to the previous heating season.

The limited academic literature on the subject highlights the range of factors which large variability in prices for biomass for space heating. Akhtari et al., (2014) point to the variation in cost depending on different types of supply chain, with transportation costs having the largest single impact. Jeswani et al., (2019) estimate that biomass boilers with the now withdrawn renewable heat incentive (RHI) subsidy were 52% cheaper than gas boilers, although without are 23% more expensive. Jablonski et al., (2008) outline how demand for bio-heat in the UK residential sector could in future reach ranges between 3% (conservative estimate) and 31% (optimistic estimate) of the total energy consumed in the heat market. Moreover, economic theory suggests that with high levels of increased demand, wood fuel prices could continue their recent price increases, especially in a situation of constrained supply (Labandera et al., 2017).

[4] https://cdn.forestresearch.gov.uk/2022/11/TPI_Sep_22.pdf
[5] https://www.fitzpatrick-fuels.co.uk/Solid-Fuel-Price-Increases

2.2 Greenhouse gas emissions

Many national and international policy frameworks, including the UK and the EU, consider wood fuel as zero-carbon at the point of combustion. That is, wood is classified as renewable energy and hence eligible for any financial or regulatory support as are other sources of renewable energy. This assumes that CO_2 emissions released in wood combustion are sequestered back into growing trees.

However, critiques exist regarding this assumption of carbon neutrality. One reason is the time lag between CO_2 emissions from burning and carbon sequestration back into growing biomass, i.e., CO_2 molecules spend time in the atmosphere where they contribute to global warming (Cherubini et al., 2011). Also, potential foregone sequestration is not considered; that is without harvesting, forests and soils absorb more CO_2 which wouldn't have reached the atmosphere causing global warming (Helin et al., 2016). Forest harvesting likely increases the surface albedo of the area, i.e., more sunlight is reflected and the climate cooled – however, this is more than offset by the warming effect of black carbon - tiny particles that absorb sunlight and hence have a warming effect, particularly pronounced in snow areas, ascribing a net warming potential to wood burning (Arvesen et al., 2018). A study in Australia showed that emissions from wood heating cause a larger climate impact than those from gas heating or reverse cycle air conditioning (Robinson, 2011).

Waste wood is the least concerning type of wood to burn from a carbon point of view as it would have otherwise decayed naturally or be burnt as waste and likewise release it stored carbon. Emissions might still be associated with transport, for example, albedo effects are just as valid, and the carbon might have been released more slowly if left to decay naturally. Also, there is a risk that waste wood is contaminated with e.g., glue and varnishes, which creates additional air pollution (Gehrmann et al 2020). Wood pellets have a higher emission factor than wood logs (DEFRA, 2022).

In addition to CO_2, wood stoves emit the greenhouse gases methane (CH_4) and nitrous oxide (N_2O). Methane is the second most important greenhouse gas contributor to climate change; its global warming potential is 27-30 times higher than CO_2, and N_2O is 273 times higher on a 100-year time scale. Gas boilers emit CO_2 and methane. For heat pumps, the greenhouse gas emissions depend on the electricity used to power them with the additional risk of leakage from refrigerant that have a high warming potential. However, due to a lack of data, a low incidence rate and improvement of refrigerants these are not usually modelled.

Acknowledging concerns around the assumption of carbon neutrality of wood burning, in this study we use emission factors as used in the Standard Assessment Procedure (SAP) as used by the UK government (BEIS, 2022). This assumes of carbon neutrality for wood burning. The value given for wood logs combines Scope 1 emissions that derive from combustion itself and for wood are methane and nitrous oxide and Scope 3 emissions, i.e., the well-to-tank emissions for emissions from processing and transporting fuel

(DEFRA, 2022). However, this means that the findings around greenhouse gas emissions need to be heavily caveated, given the concern around carbon neutrality of wood. The out-of-scope emissions give an indication of the actual carbon dioxide emitted upon combustion (DEFRA, 2022).

2.3 Air pollution

Burning of solid fuels, such as wood and wood products creates a range of pollutants including particulate matter, nitrogen oxides, sulphur oxides, carbon monoxide, volatile organic compounds, dioxins, and furans. Particulate matter (PM) refers to microscopic particles suspended in air that are created through combustion or friction (e.g., braking). They are also created through atmospheric chemical reactions between air pollutants. PM is classified by size range into coarse particles (PM10-2.5), fine particles (PM2.5) and ultrafine particles (PM0.1).

Overall, for both PM10 and PM2.5, the UK's observed values were within the annual limit values (40 µg/m3 and 20 µg/m3 respectively) in 2021. However, several UK sites exceeded the more stringent targets of the World Health Organization (WHO) of 15 µg/m3 and 5 µg/m3 respectively (Blake & Wentworth, 2023). It is important to stress that evidence indicates there is no safe threshold in the health effects of fine particles, i.e., there is no safe level of PM exposure so targets could be 0 µg/m3 (Velasco and Jarosińska 2022). For nitrogen oxide (NO_2), the UK has breached its legal limit of 40 µg/m3 in multiple areas, especially in large urban centres. Domestic combustion is a major source of particulate matter emissions, e.g., in 2021 it accounted for 16% of PM10 emissions and 27 % of PM2.5 emissions (DEFRA, 2023a). Wood burning specifically is responsible for the largest share of these, i.e., about 21% for PM 2.5 emissions. PM 2.5 emissions from domestic wood burning have increased by 124% between 2011 and 2021. PM 2.5 is generally given most attention as it is considered the worst of the pollutants from a health perspective (Sigsgaard et al., 2015).

Wood burning specifically is responsible for 23–31% of PM 2.5 in London and Birmingham (Font & Fuller, 2017) with rural areas having much lower shares of about 4-6%. Winter pollution is naturally much higher than summer pollution and pollution levels are higher in evenings and weekends, indicating residential usage. Similar values are reported from other European countries such as Denmark and Norway, with values reaching more than 50% in some Alpine valleys (Sigsgaard et al., 2015). For NO_2, domestic combustion only plays a subordinate role; for sulphur dioxide (SO_2) domestic burning accounts for 25% of all emissions (DEFRA, 2023b), however, wood only emits very small amount compared to coal. Emission factors vary significantly depending on wood type, combustion equipment and operating conditions (Vicente & Alves, 2018).

Particulate emissions are significantly higher for fuels with higher moisture content (Price-Allison et al., 2019). Fresh cut wood cut has about 50% moisture; thoroughly dried wood about 15-20% (Williams et al., 2012). Different types of stoves are associated with very different emission rates, with older stoves performing much worse (Johansson et al., 2004). To account for this dependency on stove type, in this study we model three different types using average emission values as given in the EMEP/EEA air pollutant emission inventory guidebook 2019 (see section 4.5.1 for greater details).

2.4 Health impacts

According to the World Health Organization air pollution is associated with 7 million premature deaths annually; estimates in the UK range from about 29,000 - 43,000 deaths every year[6]. Estimates put the costs to the NHS and social care system between 2017-2025 or fine particulate matter and nitrogen dioxide at about £1.6 billion (OHID, 2022). Air pollution is modelled to be responsible for 2.4 million new cases of disease in England between 2019 and 2035, with PM 2.5 causing 350,000 cases of coronary heart disease and 44,000 cases of lung cancer in England (DEFRA, 2019).
Long-term exposure to air pollution contributes to chronic conditions, e.g., cardiovascular and respiratory diseases and lung cancer. Short-term exposure to high levels of air pollution is typically associated with acute health outcomes, such as exacerbation of asthma, increases in respiratory and cardiovascular hospital admissions and mortality. Young children, the elderly, and those suffering from breathing problems like asthma are particularly affected (Chakraborty et al., 2020). Summarizing a recent government briefing document (Blake & Wentworth, 2023), the following health effects in Table 1 are linked to air pollution, in particular, particulate matter.

Table 1 Acute and chronic effects of air pollution.

Acute effects	Chronic effects	Emerging evidence
Strong evidence		
• Worsening of asthma and chronic obstructive pulmonary disease • Coughing, wheezing and shortness of breath • Acute cardiovascular effects including heart attacks and strokes	• Development of cardiovascular diseases • Development of lung diseases, including lung cancer • Dementia and cognitive decline	• Development of respiratory conditions such as asthma • Pregnancy loss, low birth weight and other adverse birth outcomes • Type II diabetes • Infertility • Some cancers (such as kidney, bladder) • Increased Covid-19 severity • Cognitive performance

The UK Government publishes air pollution damage costs to allow assessing the air quality impact of policies or projects expressed as monetary impact values per tonne of

6 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1083447/CHaPR_AQ_Special_Edition_2206116.pdf

emission or kWh energy used (DEFRA, 2023a). These are generally conservative estimates and only included directly attributable health impacts. In addition to central damage costs, a low and high value of damage costs is given, see section 5.3. Incorrectly installed wood burners can lead to carbon monoxide poisoning as can gas stoves (Cushen et al., 2019) and pose a fire risk. However, given the low incidence rates, these possible outcomes are not modelled. Moreover, wood, particularly waste wood, can contain harmful components when burned and this has not been factored into the health costs due to insufficient data. For example, researchers at Imperial College identified arsenic among the chemicals from woodsmoke, thought to have been the result of burning waste wood during Winter 2022.[7]

[7] https://www.theguardian.com/environment/2023/feb/09/arsenic-london-air-burning-waste-wood

3 Dynamic simulation methodology using Design Builder.

In the following section we set out details of the reference dwelling, our dynamic simulation modelling approach using Design Builder software, and the 10 modelling scenarios.

3.1 Reference dwelling

To model the economic, environmental health and social impacts of domestic wood burning stoves, we first needed a reference dwelling. Given the focus on an urban environment such as London, and with around 32% of London's homes built before 1919[8], we opted for a typical 3-bedroom mid-terrace late Victorian dwelling, shown in Figure 1. The building of approximately 136m² is of a typical London vernacular with a mid-twentieth century rear extension and up to three existing fireplaces that could be inexpensively converted to a wood burner. Here we assume the house has a basic level of energy efficiency with loft insulation and double-glazed windows. However, we assume that the solid walls and floors remain uninsulated. A summary of the thermal parameters is provided in
Table 2.

Building Element	Description	Thermal Parameters
Walls	Solid Brick, single skin, uninsulated	U-value 2.0 W/m2K
Floors	Suspended timber, uninsulated	U-value 0.5 W/m2K
Roof	Cold roof, 300mm mineral wool insulation	U-value 0.15 W/m2K
Windows & Doors	Double glazed, UPVC	U-value 1.8 W/m2K
Air Permeability	Typical of this period	1.0 air changes/hour

Table 2 Reference dwelling thermal parameters

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[8] https://data.london.gov.uk/dataset/property-build-period-lsoa

3.2 Modelling input assumptions

A key aim was to model different occupancy and behavioural assumptions surrounding the use of wood burners as compared to other types of heating system. To this end we modelled two occupancy scenarios. Scenario 1 is designed to show a higher use case where more of the rooms in the home are heated to a comfortable temperature throughout the day. Scenario 2 is a lower use case where heating is switched off in

Figure 1 Reference 3-bedroom mid-terrace dwelling

unused rooms such as bedrooms. A narrative description of these scenarios is outlined below, with details of the heating programme shown in Table 2.

Occupancy Scenarios 1 & 2

1. Family of four, one parent works full-time out of the house, the other part-time from home.
   Children are at school most days. Heating is needed across the house to keep warm when everyone is home and in different rooms (typically 7-9am and 6-9pm) and to dry laundry/towels
2. Older couple, both retired and spend most of the day at home/in the neighbourhood. Heating is needed to keep warm all day in the main room (9am-5pm) and in the bathroom and bedroom as well first thing in the morning and in the evening (typically 7-9am and 6-9pm). Couple have a tumble drier.

Heating System Options A-E

We then paired these occupancy scenarios with five different heating system configurations (A-E). These take natural gas central heating as the status quo, before modelling a range of wood burner configurations. As a further comparison we also modelled an air source heat pump (ASHP). These options are described below, with the specific heating patterns detailed in Appendix 1.

a. **Existing natural gas led heating providing 100% of heat**
   In Option A we assume an existing condensing gas boiler provides all the homes heating and hot water.
b. **New woodburning stove led heating (80%) with natural gas secondary heating (20%)**
   In Option B we assume that two new woodburning stoves are installed (likely on the ground floor) which are used to provide 80% the homes space heating. The gas boiler is used only for 20% of heating needs to heat peripheral rooms and for hot water.
c. **Existing natural gas led heating (80%) with new wood burner secondary heating (20%)**
   In Option C we assume only one woodburning stove is installed which provides 20% of heat demand to the communal living room on the ground floor. The majority (80%) of rooms are heated by a gas boiler, which also provides hot water.
d. **Existing natural gas led heating (80%) with existing wood burner secondary heating (20%)**
   Option D is the same as Option C except we assume the wood burner is pre-existing.
e. **New Air Source Heat Pump (ASHP) providing 100% of heat**
   Option E involves the installation of an ASHP with new cylinder, radiators, and controls. We assume the ASHP provides all heating and hot water for the home.

3.3 Dynamic simulation model using DesignBuilder

Energy demand calculations were carried out as an hourly dynamic simulation for a whole year, using CIBSE TRY (Test Reference Year) weather data for London, and the software DesignBuilder. Dynamic thermal simulation is a computational simulation of building where the energy balance of each building zone is calculated for each hour of the simulation period and all aspects which affect the balance are accounted for, including building fabric and thermal mass; solar irradiance including typical clouds; overshading by surrounding buildings; occupancy patterns; lighting; internal heat gains from equipment; ventilation. The combination of these occupancy scenarios and heating system options produces a total of 10 different scenarios as shown in Table 3.

3.4 Model outputs

The options and scenarios outlined in Appendix 1 were modelled for a full calendar year using the DesignBuilder software. This produced heat energy demand profiles for each of the 10 options as shown Table 3 and Figure 2. The table and figure show that, as expected, heat and water energy demand is 10% lower in Scenario 2, where fewer rooms are heated. The data also highlights how the three-wood burner options consumer more fuel energy due to the lower conversion efficiency of woodburning stoves, whereas the ASHP has a far lower energy demand, due to its seasonal coefficient of performance (SCoP) of 3.5 or a 350% efficiency.

Table 3 Heat energy outputs across all scenarios

		Option 1A	Option 1B	Option 1C & 1D	Option 1E
Scenario 1 - Family of Four		kWh/year	kWh/year	kWh/year	kWh/year
	Gas consumption	12,379	2,491	10,220	-
	Wood consumption	-	10,187	2,224	-
	Electricity for ASHP	-	-	-	3,006
	Total space heating	12,379	12,678	12,444	3,006
	Total Water Heating	2,738	2,738	2,738	2,738
Scenario 2 - Older Couple		Option 2A	Option 2B	Option 2C & 2D	Option 2E
		kWh/year	kWh/year	kWh/year	kWh/year
	Gas consumption	11,087	2,167	8,920	-
	Wood consumption	-	9,190	2,233	-
	Electricity for ASHP	-	-	-	2,693
	Total space heating	11,087	11,357	11,153	2,693
	Total Water Heating	1,870	1,870	1,870	1,870

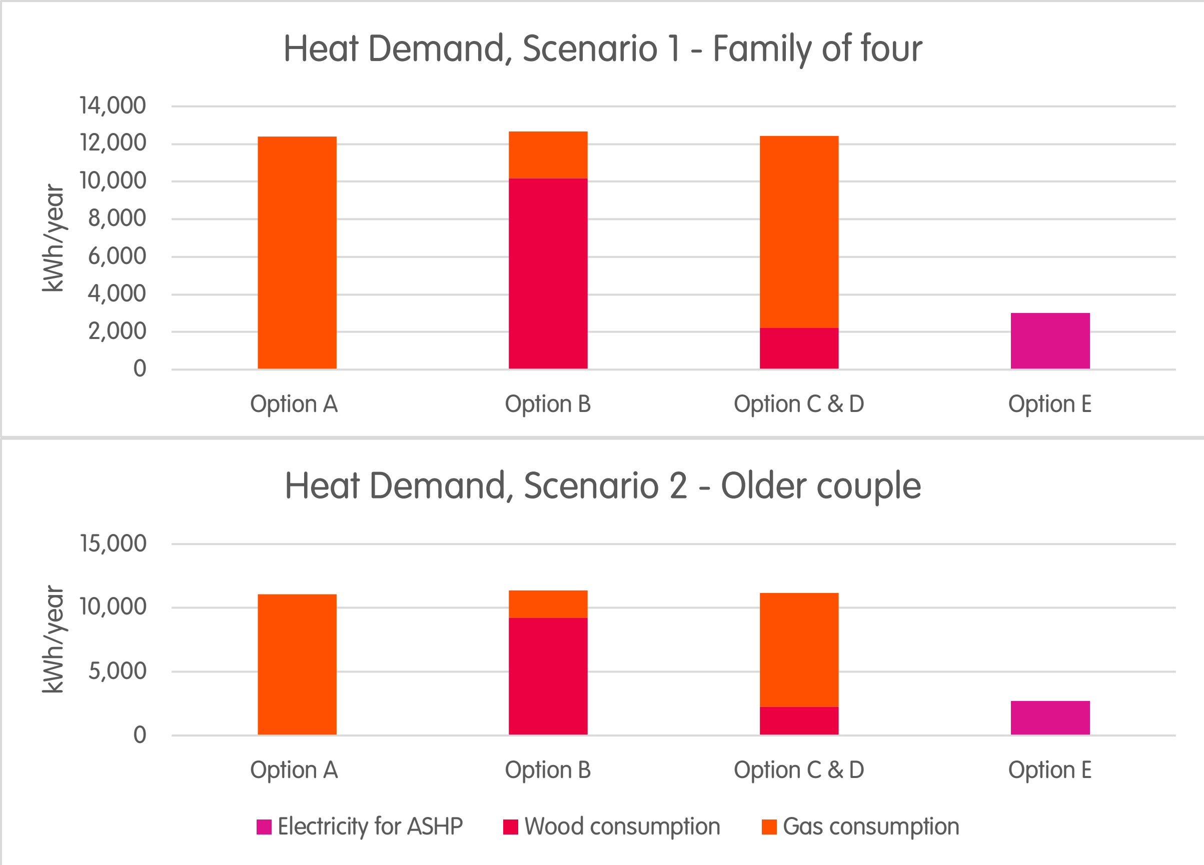


Figure 2 Energy outputs across all scenarios

4 Economic, Environmental, Social and Health impacts of these scenarios.

Drawing on the literature review, in this section we quantify the cost, environmental, social and health implications of woodburning for the households, and the wider environment and society, using a mix of quantitative indicators. This is presented in a disaggregated form, highlighting the expected impacts across a range of indicators, showing different impacts on their own terms, before aggregating them into a cost impact figure in Section 5. This allows discussion of nuances surrounding the ranges and uncertainties in impacts.

4.1 Natural gas & electricity prices

The recent period has seen unprecedented increases in domestic energy costs, largely driven by wholesale gas prices. This makes accurate energy price predictions fraught with difficulty. Acknowledging these limitations, we estimate future prices for a 15 year period (2023-2038), using data from the latest Ofgem price cap announcement, the Cornwall Insight[9] 2023 price cap predictions, and personal correspondence[10] with Cornwall Insight. The UK government recently froze average domestic energy prices to £2,500 from the 1st of October 2022 until June 2023 - an electricity unit rate of £0.34/ kWh and a gas unit rate of £0.103/kWh. We then expect prices to fall by the end of 2023 before a return to the background price inflation trend of 3% for energy bills (Figure 3). These 15-year price projections are therefore used in the life cycle cost projections developed in Section 5.

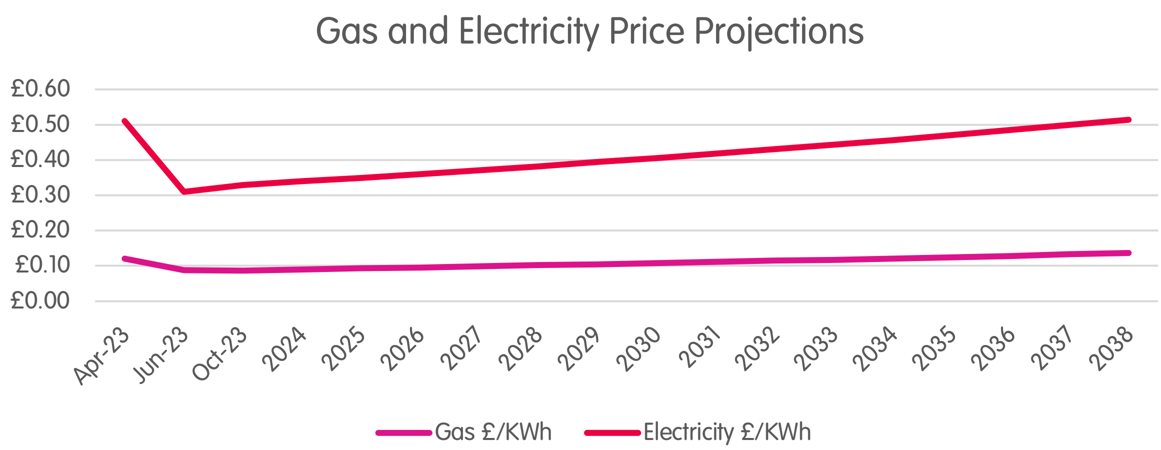


Figure 3 Gas and electricity price projections

[9] https://www.cornwall-insight.com/press/cornwall-insight-forecasts-a-fall-in-the-april-2023-price-cap-but-prices-remain-significantly-above-the-energy-price-guarantee/

[10] Energy prices to remain significantly above average up to 2030 and beyond: https://www.cornwall-insight.com/press/energy-prices-to-remain-significantly-above-average-up-to-2030-and-beyond/

4.2 Wood log prices

While current gas and electricity prices are easy to determine and are heavily regulated, the unit price of wood logs today has much greater variability. A report by the Stove Industry Alliance (SIA) and Gemserve recently claimed that:

> "Wood logs are now the cheapest domestic heating fuel, costing households 74% less per kWh than electric heating and 21% less than gas heating. Using a modern wood burning stove also costs 29% less to run than an air source heat pump".
> *(SIA Press Release)*

The SIA source their pricing from Nottingham Energy Partnership[11], who provide monthly updates on a range of energy prices. This source estimates kiln dried wood logs to currently cost around £0.40/kg or £0.095/kWh, based on an energy content of 4.2kWh/kg. This would suggest that wood logs are marginally cheaper than natural gas for heating, although the figures they cite do not factor the energy price freeze. We therefore sought to verify this against some other sources, to provide a comparison to the SIA claims. However, after an extensive search, we could not find any secondary sources that have done recent market research on the issue in the UK.

We have therefore undertaken our own primary research, via a "mystery shopper" type exercise to examine different prices for wood logs. This included both online and in person research at various locations around southeast London, on the 16th of February 2023. The results from 14 sources are shown in Figure 4. As you can see from the chart the SIA source and a similar Money week/HETAS[12] source (grey bars), assumes a cost around £0.09-0.1/kWh. The online bulk purchase options (amber) show a range £0.09-0.17/kWh, while the specialist online single bag purchase options show a similar range. The red bars are all single bag, in person purchases from garages, DIY stores and garden centres. As you can see, this type of fuel purchase is considerably more expensive than the online options, with one garage over four times the quoted cost from the SIA study.

[11] https://nottenergy.com/resources/energy-cost-comparison/
[12] https://moneyweek.com/personal-finance/605530/wood-burning-stove-vs-central-heating

Figure 4 Wood log price comparison, using third party, bulk, online and in person research

Therefore, our research highlights that the affordability of wood fuel for home heating depends largely on where the wood is sourced from. Recent research for DEFRA by the consultancy Kantar provides an indication of the relative fuel mix for UK wood burners. As shown in the Kantar data in Table 4 below, around 19% of users buy wood from general, non-specialist suppliers (garages & garden centres etc.) while 31% comes from specialist suppliers and the rest from a range sources. To simplify this picture, we categorise the sources in the table as low cost (green), medium cost (amber) and high cost (red) sources.

Table 4 Wood fuel mix by source. Adapted from Kantar Research

	Wood Only *Market share 47%*	**Wood Mix** *Market share 53%*	**Total**
Specialist supplier	38%	26%	31%
General supplier	24%	14%	19%
Given by friends / family	7%	15%	11%
From own garden	7%	17%	12%
Bought from landowner or farmer	11%	12%	12%
Salvaged wood	3%	11%	7%
Fallen wood from trees in public places	3%	4%	3%
Online	1%	0%	0%
Other	3%	1%	2%
None of the above	4%	0%	2%

- **Low-cost timber from own/free supply**, friends, family, or via salvage >0.05p/kWh. Kantar suggests about 34% of wood only burners are supplied via this route, most of the cost is therefore kindling and firelighters. We might expect this % to be much lower in urban locations.
- **Medium cost via specialist online suppliers** - 0.09-0.17p/kWh - Kantar suggests 48% of wood burners are supplied via this bulk purchase route. This could also be assumed to be lower given the storage challenges urban dwellers are likely to face.
- **High cost, via non-specialist suppliers** - >0.25p/kWh - Kantar assumes this is 19% of the market, although we might expect this to be much higher in urban locations and among occasional users. Table 5 we outline Low, Medium, High wood fuel price scenarios, based on average values from our market research. Using the relative market share we subsequently arrive at a central price based on the relative contribution from these sources.

Table 5 Low, Medium, High and Central wood fuel price scenarios

	Description	£/kWh	Market share
Low Price	Kindling and firelighters only	£0.03/kWh	34%
Medium Price	Online, bulk purchase	£0.14/kWh	48%
High Price	In store, non-specialist, single bag	£0.33/kWh	19%
Central Price	Average price of mixed fuel sources	0.14/kWh	100%

4.3 Capital expenditure (CAPEX)

To model the net present cost of the various system configurations we must first include the capital cost of the various system options. Option A the gas boiler assumes the system is halfway through its functional life span and therefore must be replaced in year 8. Option B assumes in addition to the gas boiler, two woodburning stoves are installed in year 1. Option C assumes only one wood burner is installed in year 1, alongside the replacement boiler. Option D is the same as option A, as we assume the wood burner is pre-existing. For option E we assume a new ASHP install in year 1 with new radiators and controls; here we also assume the ASHP is eligible for the boiler upgrade scheme grant. These CAPEX assumptions are shown in Table 6.

Table 6 CAPEX assumptions

	CAPEX	Notes	Source
Option A	£2,900	Gas boiler is replaced in year 8, with £2,500 cost adjusted for RPI 2% (assuming an average 15-year life)	• https://www.checkatrade.com/blog/cost-guides/new-boiler-cost/
Option B	£5,900	2 new wood burners installed at £1,500[13] each Gas boiler is replaced in year 8, with £2,500 cost adjusted for RPI 2% (assuming an average 15-year life)	• https://www.checkatrade.com/blog/cost-guides/log-burner-install-cost/ • https://www.checkatrade.com/blog/cost-guides/new-boiler-cost/
Option C	£4,900	1 new wood burner is installed at £2,000 Gas boiler is replaced in year 8, with £2,500 cost adjusted for RPI 2% (assuming an average 15-year life)	• https://www.checkatrade.com/blog/cost-guides/log-burner-install-cost/ • https://www.checkatrade.com/blog/cost-guides/new-boiler-cost/
Option D	£2,900	Gas boiler is replaced in year 8, with £2,500 cost adjusted for RPI 2% (assuming an average 15-year life)	• https://www.checkatrade.com/blog/cost-guides/new-boiler-cost/
Option E	£8,000	ASHP System install cost is £13,000 including new radiators Minus £5,000 Boiler Upgrade Scheme grant	• https://www.checkatrade.com/blog/cost-guides/air-source-heat-pump-cost/ • https://www.gov.uk/apply-boiler-upgrade-scheme/what-you-can-get

[13] Here we assume a substantial discount vs the average quotes wood burner installs, assuming 2 are installed.

4.4 Operating expenditure (OPEX)

For operating expenditures, we exclude fuel costs as they are accounted for in the energy model. For Option A we assume boiler cover and an annual service. For Option B we assume an additional chimney sweep for each wood burner, alongside the boiler service. Option C has only one chimney sweep per year, as does Option D. Option E involves an annual service for the ASHP only, with an additional £0.30/day saving from the gas standing charge disconnection. These OPEX assumptions are shown in Table 7.

Table 7 OPEX assumptions

	OPEX	Notes	Source
Option A	£4,150	Annual boiler service and cover starting at £240/year and increasing with RPI target of 2%	• https://www.checkatrade.com/blog/cost-guides/boiler-service-cost/
Option B	£6,744	2X annual chimney sweep at £150 increasing with RPI target of 2% Annual boiler service and cover starting at £240/year and increasing with RPI target of 2%	• https://www.mybuilder.com/pricing-guides/chimney-sweep-costs • https://www.checkatrade.com/blog/cost-guides/boiler-service-cost/
Option C	£5,447	We assume an annual boiler service and cover starting at £240/year and increasing with RPI target of 2% 1X Annual chimney sweep at £75, increasing with RPI target of 2%	• https://www.mybuilder.com/pricing-guides/chimney-sweep-costs • https://www.checkatrade.com/blog/cost-guides/boiler-service-cost/
Option D	£5,447	We assume an annual boiler service and cover starting at £240/year and increasing with RPI target of 2% 1X Annual chimney sweep at £75, increasing with RPI target of 2%	• https://www.mybuilder.com/pricing-guides/chimney-sweep-costs • https://www.checkatrade.com/blog/cost-guides/boiler-service-cost/
Option E	£925	We assume an annual service for the 15-year life of the ASHP at £163 and increasing with RPI target of 2% £0.3/day saving from gas standing charge disconnection, increasing with RPI target of 2%	• https://les.mitsubishielectric.co.uk/assets/Uploads/cbce9e3316/MELSMART-SERV-MAINT-HOMEOWNER.pdf

4.5 Environmental inputs

4.5.1 Air pollution

The air pollution values are taken from the EMEP/EEA air pollutant emission inventory guidebook 2019 (emep, 2019), (Tables 3.40, 3.41, 3.42, and 3.16). Since air pollution damage costs are only given for a subset of pollutants, we focus on PM2.5, PM10, NOx and SOx. Figure 5[14] shows the mean emissions and 95% confidence interval of these pollutants from different heating appliances.

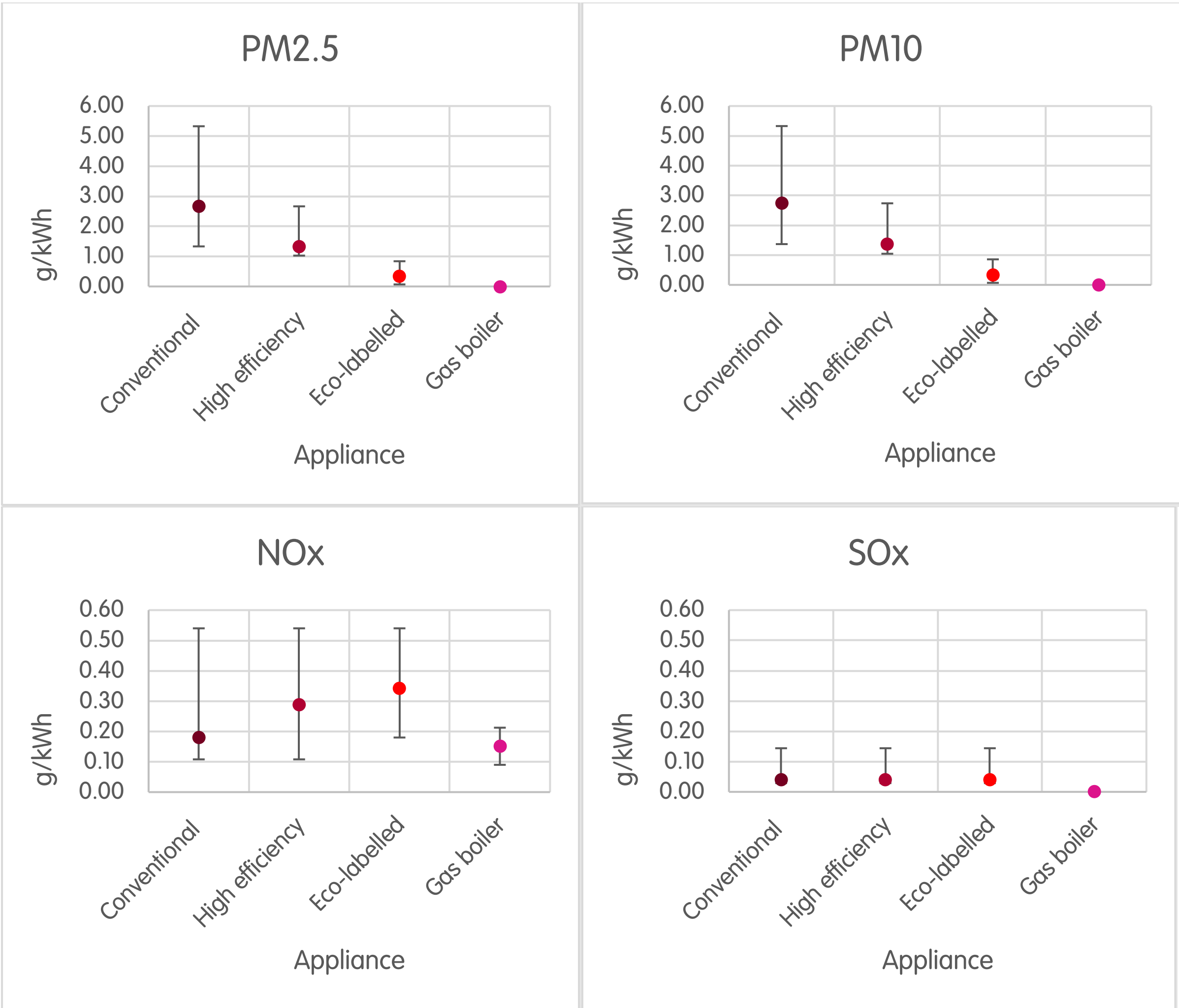


Figure 5 Mean emissions and 95% confidence interval of PM2.5, PM10, NOx and SOx from different heating appliances. Source: EMEP/EEA air pollutant emission inventory guidebook.

Three things stand out from these graphs: (1) Gas boilers have generally lower emission rates than wood stoves. (2) The type of wood stove used is hugely important especially regarding particulate emissions (PM 2.5, PM10). (3) The 95% confidence intervals around the mean are very large, meaning that for any particular stove use, emissions could be much higher. For modelling purposes, we are using the mean estimates, but it is essential to consider that actual emissions could be much higher depending on the burning practices and wood moisture content.

[14] Note that for comparability purposes across appliance type, the axis range varies in the upper and lower graphs.

4.5.2 Greenhouse gas emissions

For the assumptions of greenhouse gas emissions associated with home heating, we employ the emission factors as given in SAP 10.02, table 12. The Standard Assessment Procedure (SAP) is the methodology used by the UK government to assess and compare the energy and environmental performance of dwellings. The values given are CO_2 equivalent figures (CO_2e), i.e., in addition to CO_2, they include the global warming impact of CH_4 and N_2O. The emission figures Scope 3 emission, i.e., emissions that happened along the supply chain prior to combustion. Figure 6 shows the greenhouse gas emissions for various fuel types; in this report, only gas, wood logs and electricity are considered in the modelling; the pattern-filled bars show other solid fuels potentially used in home heating for comparison purposes.

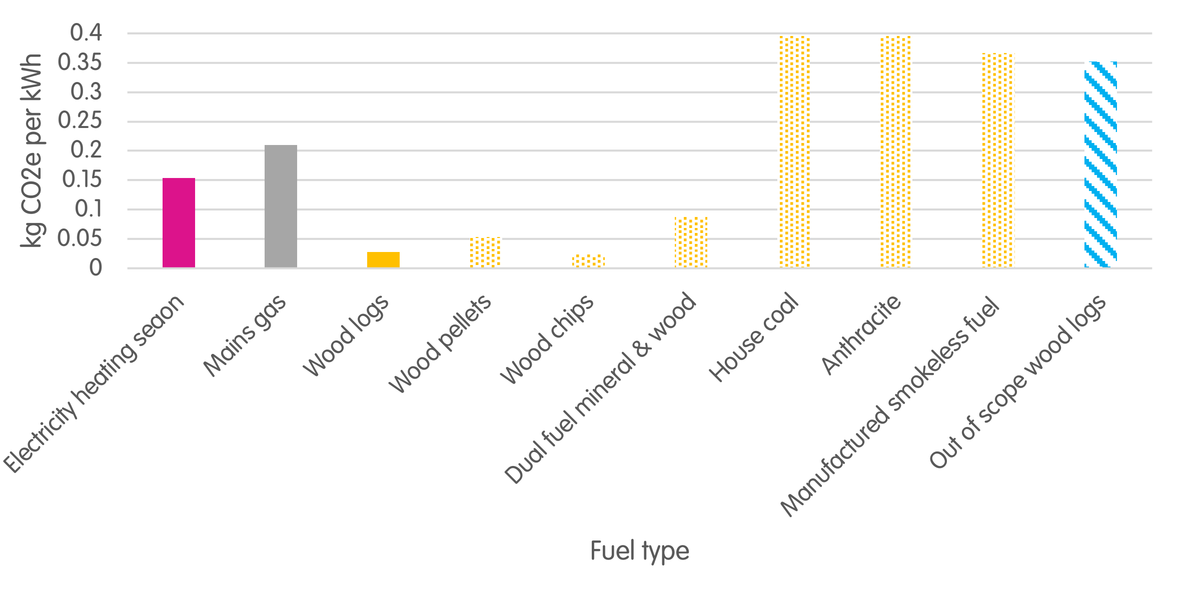


Figure 6 Emission factors for various fuels expressed in kg CO2 per kWh. Source: Table 12, SAP version 10.2. Out of scope emissions retrieved from UK Government GHG Conversion Factors for Company Reporting

Out of scopes includes biogenic CO_2 factors that should be used to account for the direct CO_2 impact of burning biomass. Biogenic CO_2 emissions are labelled 'outside of scopes' by the GHG Protocol Corporate Accounting and Reporting Standard because the Scope 1 impact of these fuels has been determined to be a net '0' (since the fuel source itself absorbs an equivalent amount of CO_2 during the growth phase as the amount of CO_2 released through combustion). Hence, they are only reported here for information's sake but are not further included in the modelling work. However, it is important to keep in mind that biomass cannot be by default considered carbon neutral (Swackhamer & Khanna, 2011). Whether it is truly carbon neutral depends on the time frame being studied, type of biomass is used, combustion technology, what forest management techniques are employed in the areas where the biomass is harvested. Biomass needs to be managed and harvested in a sustainable way to be considered a carbon-neutral fuel. Heat pumps *per se* are considered a renewable energy source; however, they need electricity to be operated which may or may not be carbon neutral. For the purpose of the modelling exercise, we use the CO_2 value for electricity as provided in SAP which is based on a 5-year projection for 2020-2025. The carbon intensity varies depending on the month under consideration; here, we use the average for an assumed heating season of October to March, 0.154 CO_2e/kWh, based on monthly values given in SAP Table 12.d. Heat pumps historically used refrigerants, hydrofluorocarbons (HFCs) that are potent greenhouse gases with a global warming potential of over 1000 times that, of CO_2. Leakages might occur in 3-5% of domestic installations; however, modern heat pumps use refrigerants with less global warming potential (DECC, 2014; Singh Gaur et al., 2020; Zanchi et al., 2019). Hence, for the modelling conducted here, it is assumed that no leakages occur, because of how rare they are but also because the of the low expected impact of modern refrigerants.

4.5.3 Future CO_2e emissions and carbon prices

For gas and wood, we assume static assumptions about their carbon intensity. Whilst this is a simplification, e.g., given ongoing decarbonization of transport and industrial processes, it is justified by the fact that the greatest share of CO_2e for wood and gas results from combustion of the fuel which will not change. However, the carbon intensity of electricity will likely change significantly over the modelled 15-year horizon. The UK government is now targeting total decarbonisation of the electricity system by 2035. Therefore, to model the reducing grid carbon factors (tCO_2e/kWh) we adopt an average of the National Grid Future Energy Scenarios (FES)[15] from 2023 to 2038. Here we use a more conservative scenario which ignores the negative emissions from biomass carbon capture and storage (BECCS).

To arrive at the price of current and future CO_2e emissions, we adopt the UK government's, "Valuation of greenhouse gas emissions: for policy appraisal and evaluation" approach[16]. Greenhouse gas emissions values ("carbon values") are used across government for valuing impacts on GHG emissions resulting from policy interventions. They represent a monetary value that society places on one tonne of carbon dioxide equivalent (£/tCO_2e). The new carbon values are based on a Marginal Abatement Cost (MAC) or "target-consistent" valuation approach. This involves setting the value of carbon at the level that is consistent with the level of marginal abatement costs required to reach the targets that the UK has adopted at a UK and international level. As the low hanging fruit of mitigation measures are undertaken first, these costs are seen to rise though time.

[15] https://www.nationalgrideso.com/future-energy/future-energy-scenarios
[16] https://www.gov.uk/government/publications/valuing-greenhouse-gas-emissions-in-policy-appraisal/valuation-of-greenhouse-gas-emissions-for-policy-appraisal-and-evaluation#annex-1-carbon-values-in-2020-prices-per-tonne-of-co2

4.6 Health and social inputs

The Department for Environment, Food and Rural Affairs (Defra) have developed 'damage costs' to estimate the societal costs associated with small changes in pollutant emissions (DEFRA, 2023a). Damage costs are a set of impact values, measured per tonne of emission by pollutant, which are derived using a more complex Impact Pathways Analysis (IPA) (DEFRA, 2023b). The estimation of the impacts of air pollution are inherently uncertain, for example, related to emissions dispersion modelling and the translation of changes in air pollution concentrations into impacts and how those are valued. To allow an indication of the possible variation in damage costs, an uncertainty range is given with low and high damage costs with central damage costs being the best estimate. The scenarios vary in which health costs are included; e.g. only the high damage cost includes chronic bronchitis for which there is greater uncertainty. The low, central, and high estimates also vary depending on which values of concentration response functions (CRF) are used. CRFs link a change in exposure to a pollutant to its consequent impacts by expressing a change in a health (or non-health) outcome for a given change in pollutant concentrations and are expressed in a range (Birchby, et al., 2023). Table 8[17] summarizes the health effects captured in the low, central, and high damage costs scenarios and indicates which values from the CRFs were used.

Table 8 Mapping of CRF bound chosen to each damage cost. L = low end of CRF bound. C = central point of CRF bound. H = high end of CRF bound.

		Damage cost sensitivity		
Pollutant	**Pathway**	Low	Central	High
PM2.5	Mortality (long term exposure)	L	C	H
PM2.5	Respiratory hospital admission	L	C	H
PM2.5	Cardiovascular hospital admission	n/a	n/a	C
SO2	Deaths brought forward	L	C	H
SO2	Respiratory hospital admission	L	C	H
NO2	Respiratory hospital admission	L	C	H
NO2	Cardio vascular hospital admission	n/a	n/a	C
NO2	Mortality (long term exposure)	L	C	H
PM10	Chronic bronchitis incidence	n/a	n/a	C
PM2.5	IHD (ischemic heart disease) incidence	L	C	H
NO2	Asthma (adults) incidence	n/a	n/a	C
PM2.5	Stroke incidence	L	C	H
PM2.5	Diabetes incidence	n/a	n/a	C
NO2	Diabetes incidence	n/a	n/a	C
PM2.5	Lung cancer incidence	L	C	H
NO2	Lung cancer incidence	n/a	n/a	C
PM2.5	Asthma (older children) incidence	L	C	H

[17] Reproduced in shortened from Table 6.1. from Birchby et al., (2023)

NO2	Asthma (older children) incidence	L	C	H
NO2	Asthma (small children) incidence	L	C	H
All	Productivity	L	C	H
All	Ecosystem	L	C	H

No range is expressed around the value of deaths brought forward from short term exposure and hence this value does not vary between low and high sensitivities. The effects of long-term exposure on mortality are the dominant impact captured in the damage costs. Figure 7 exemplifies for central damage costs for PM 2.5, the relative importance of different impacts. The second largest costs are associated with asthma incidence, followed by stroke incidence and ischemic heart disease (Birchby, et al., 2023).

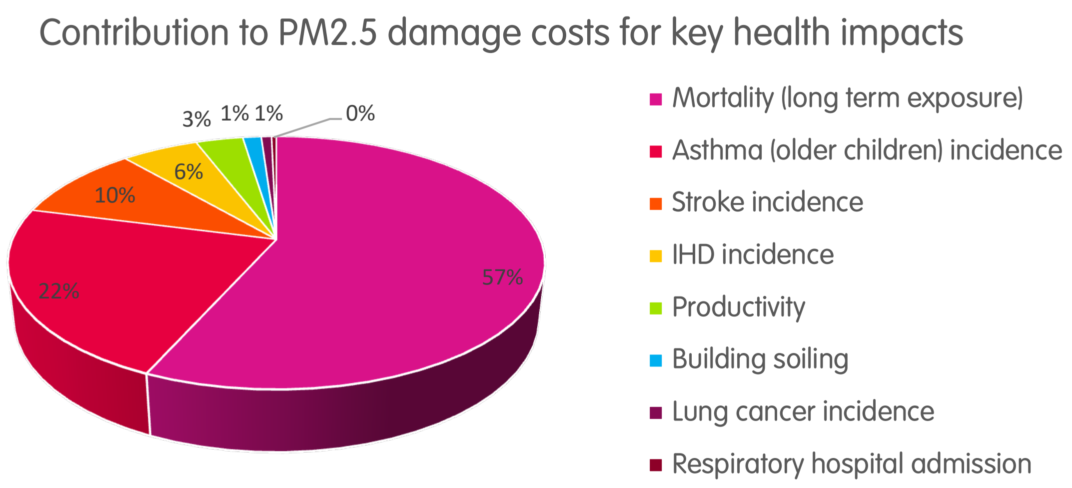


Figure 7 Contribution of multiple pathways to total central damage costs for PM2.5 exposure. Source: Table 7.4 Birchby et al., 2023).

The damage costs for the key pollutants from wood burners with the bar indicating the central damage costs and the lower error the low damage costs estimates and the upper error bar the high damage cost estimates are shown in Figure 8. Here, costs have been adjusted to reflect 2023 prices using government developed GDP deflators (HM Treasury, 2013).

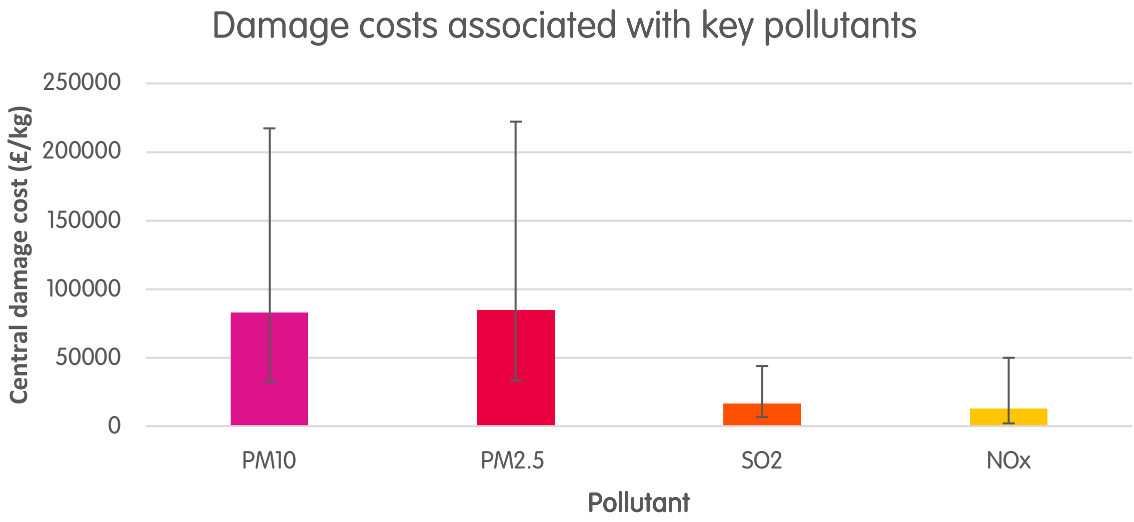


Figure 8 Central damage costs associated with key pollutants with error bars indicating low and high damage costs. Source: DEFRA Air quality damage costs.

5 Cost benefit analysis

In this section, the various environmental and social impacts are converted into cash figures and combined into a comparative cost benefit analysis. This assumes a 15-year time period, which is typical for heating ventilation and cooling (HVAC) systems. We then use this data to arrive at a Net Present Cost (NPC) for each of the options, comparing a pure economic NPC with an environmental and health NPC before combining them.

5.1 Economic costs

The two occupancy scenarios (family, retired couple) and five energy system options (A-E) were combined with the cost estimates to produce a 15-year lifecycle cost model for all 10 system permutations. For the Option A (gas boiler only) and Option E (ASHP), we modelled only a single 'central' fuel price scenario. However, for each of the wood burner options we modelled a low, medium, and high fuel price scenario from which we derived a 'central' scenario, using the methodology described in Section 4.2. These data were then combined with the CAPEX and OPEX assumptions from Table 6 and Table 7 to arrive at annual cashflow and cumulative cashflow figures for a 15 year project lifespan. The cashflow estimates were then computed to arrive at an NPC for each of the low, medium, and central price scenario estimates shown in the table and figures below. This was based on the following methods and assumptions:

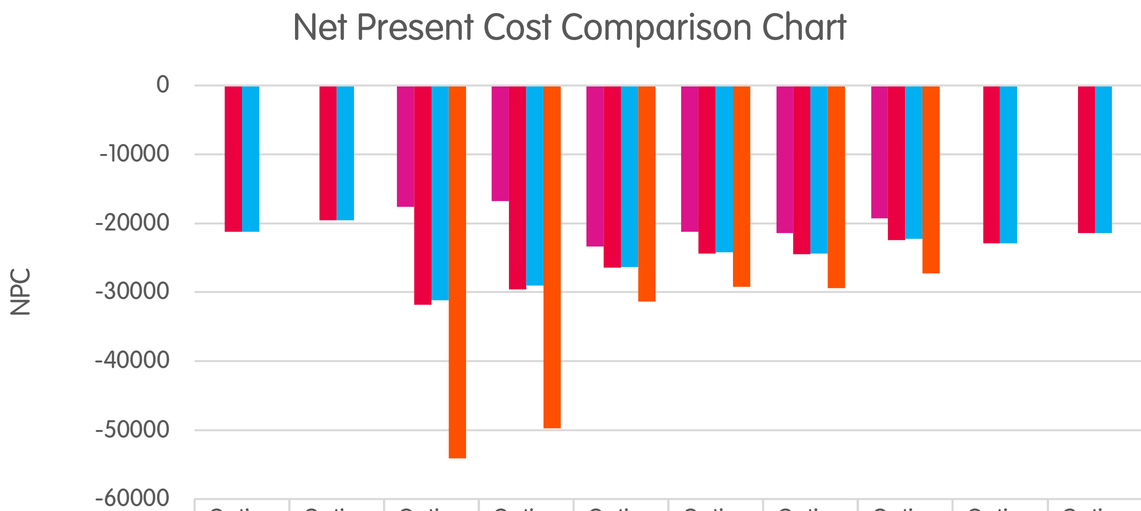
- **2% Inflation Rate**, based on the Bank of England Monetary Policy Committee target[18]
- **3% Social Discount Rate (SDR).** Discount rates are used to put a present value on costs and benefits that will occur later, with SDRs typically being lower than commercial discounting, placing a higher value on future costs. Global health evaluations typically apply a discount rate of 3% for health outcomes and costs[19]. Therefore, as our analysis forecasts a mix of economic, health and environmental costs, we propose that an SDR of 3% is appropriate.
- **Net present value (NPV)** is used to equate the total cost of a project over time to the total cost today, considering the time value of money. The present value (PV) of each annual cash flow is discounted to its PV using a suitable interest or discount rate. The NPV is determined by summing the PV for each year, staring at year 0 i.e., the investment, to the final year (N). However, for projects with no sales or incomes it is common to use **NPC**.
- **Equivalent annual cost (EAC**) is derived from the NPC, and equates to the annual cost of owning, operating, and maintaining an asset over what we assume is a 15-year life and the 3% discount rate.

Figure 9 shows the central[20] NPC of all 10 options, with the wood burner scenarios also including a low, medium, high NPC, alongside the central fuel cost scenario. In the central scenario, we observe the lowest NPCs for the gas boiler only systems (Options 1A & 2A), at an NPC of-£21,219 and-£19,585 for the 15-year lifespan of the system. This is closely followed by the ASHP system (Options 1E & 2E) at an NPC of -£22,943 and £21,435. The third cheapest system configuration is where the existing wood burner is providing secondary heating (Options 1D & 2D) at an NPC of -£24,375 and -£22,273. In the central scenario, the two new wood burner options are the most expensive (Option 1C, NPC of -£26,316 and 2C, NPC of-£24,215), with the dual wood burner dominant system (Options

[18] https://www.bankofengland.co.uk/monetary-policy/inflation
[19] https://academic.oup.com/heapol/article/35/1/107/5591528?login=false
[20] The central and medium costs are the same for the gas boiler and ASHP scenarios

1B & 2B) at an NPC of -£31,200 and -£29,039. This is 47% and 48% higher than the gas boiler only options over the 15-year lifetime.

These factors are accentuated in the high fuel cost scenarios, where the wood burner dominant system (Options 1B & 2B) has NPCs of -£54,143 and-£49,736 respectively, or total costs 155% and 154% higher than the natural gas boiler only. However, in the low fuel cost scenario, these trends are reversed. Here the wood burner dominant system configurations (Options 1B & 2B) have the lowest NPCs of -£17,568 and -£16,742 respectively, or 17% and 15% cheaper than the next cheapest gas boiler only configuration.



	Option 1A	Option 2A	Option 1B	Option 2B	Option 1C	Option 2C	Option 1D	Option 2D	Option 1E	Option 2E
	Gas Boiler only		New Woodburner 80%		New Woodburner 20%		Existing Woodburner 20%		ASHP	
NPC (low)			-£17,56	-£16,74	-£23,34	-£21,22	-£21,39	-£19,28		
NPC (medium)	-£21,21	-£19,58	-£31,80	-£29,58	-£26,44	-£24,34	-£24,50	-£22,40	-£22,94	-£21,43
NPC (central)	-£21,21	-£19,58	-£31,20	-£29,03	-£26,31	-£24,21	-£24,37	-£22,27	-£22,94	-£21,43
NPC (high)			-£54,14	-£49,73	-£31,32	-£29,24	-£29,38	-£27,30		

Figure 9 Net Present Cost (Economic) comparison across all system types, scenarios and fuel price assumptions

On an annualised basis, in our central scenarios, Option B, had an EAC of between £2,614- £2,433, around 47%-48% more than using an existing gas boiler (Option A) at £1,777-£1,641. The lower use wood burner scenario (Option C) had and EAC of £2,204-£2,028, or 24% more than the gas boiler. Even where the wood burner was existing (Option D), EACs were £2,042-£1,866, 15%-14% higher. The ASHP (Option E) EACs of £1,922-£1,796, 8%-9% higher than the gas boiler. These EACs are shown in Figure 10.

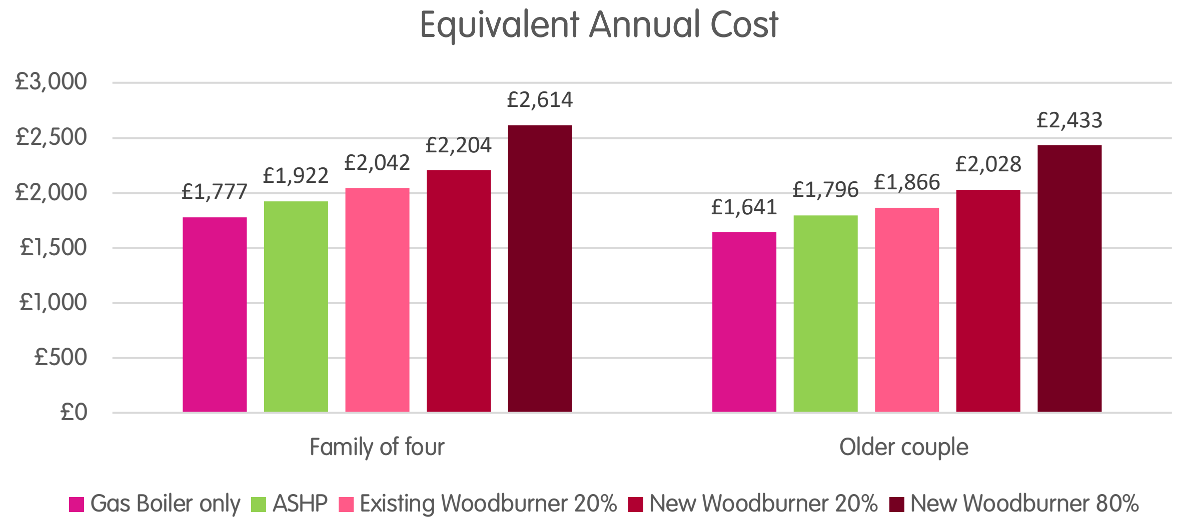


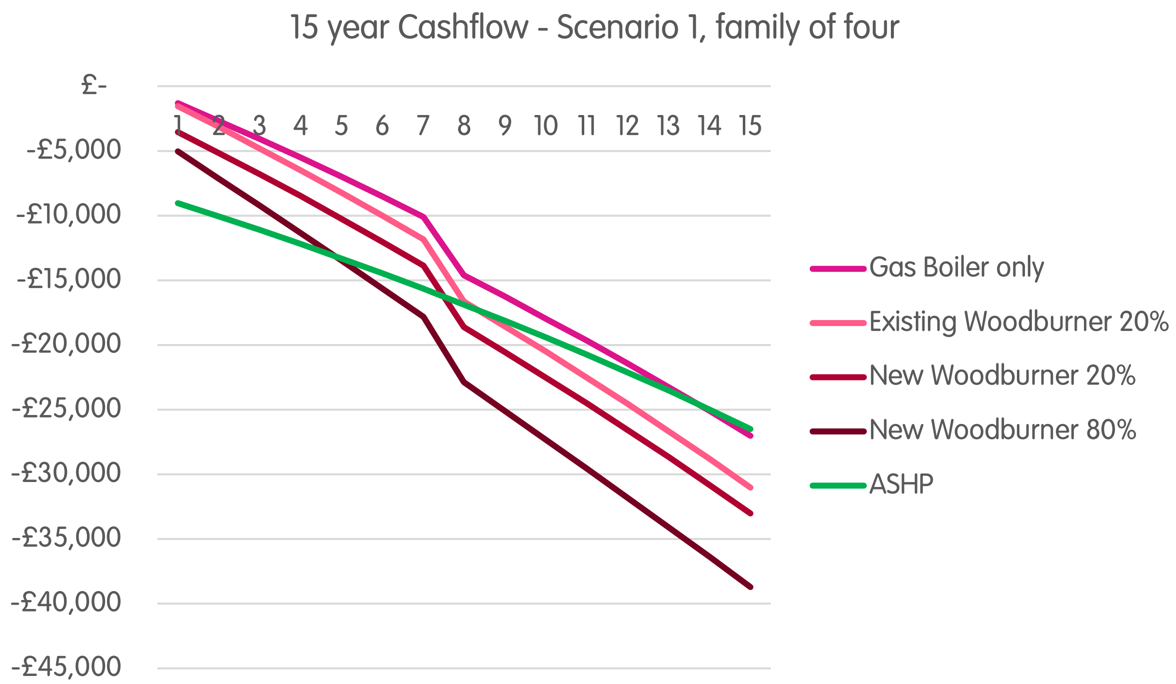
Figure 10 Equivalent Annualised Costs across all options

The full range of EAC figures for the low, high, and central cost scenarios are shown ranked in Table 9.

Table 9 Equivalent annualised costs ranked for all systems and scenarios for the low, high, and central wood fuel costs

Rank highest to lowest cost	Heating system/ pattern	Equivalent annualised costs (15 years)			
		Family of four		Older couple	
High 1	New wood burner 80%, high fuel cost	£	4,535	£	4,166
2	New wood burner 20%, high fuel cost	£	2,624	£	2,450
3	New wood burner 80%, central fuel cost	£	2,614	£	2,433
4	Existing wood burner 20%, high fuel cost	£	2,461	£	2,287
5	New wood burner 20%, central fuel cost	£	2,204	£	2,028
6	Existing wood burner 20%, central fuel cost	£	2,042	£	1,866
7	New wood burner 20%, low fuel cost	£	1,955	£	1,778
8	ASHP	£	1,922	£	1,796
9	Existing wood burner 20%, low fuel cost	£	1,792	£	1,615
10	Gas boiler only	£	1,777	£	1,641
Low 11	New wood burner 80%, low fuel cost	£	1,472	£	1,402

Figure 11 shows the undiscounted cumulative cashflows of all these options, based on the central scenario. This highlights how the capital intensive but low running cost options such as the ASHP gradually improve their cost performance over time, as compared to the higher running costs of the natural gas and wood burner options.



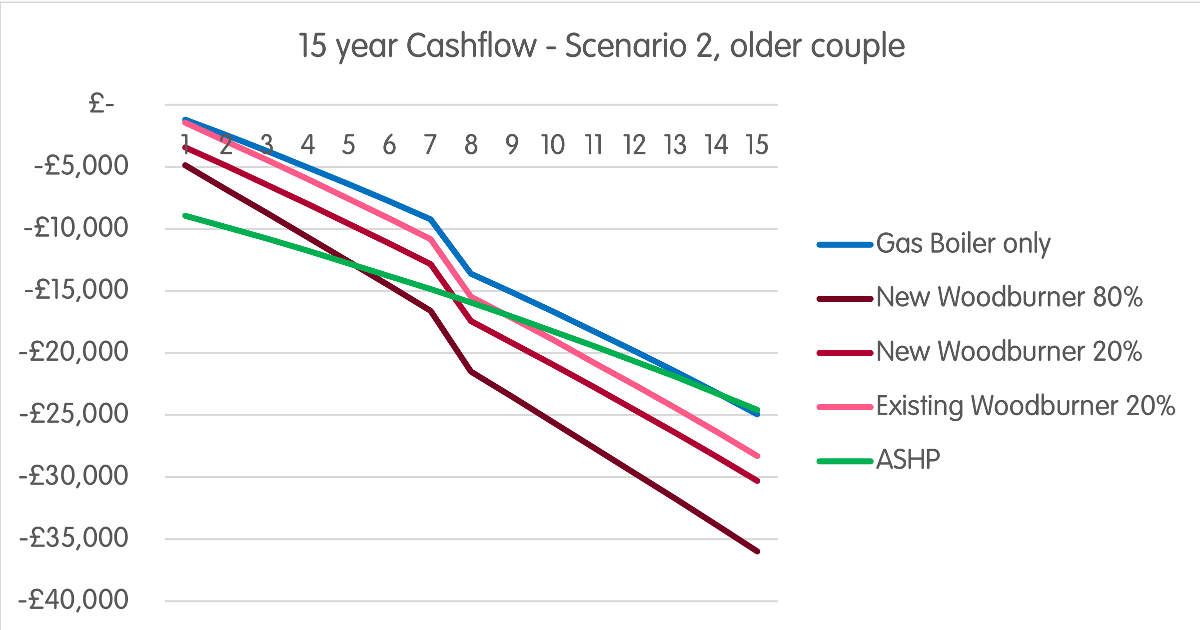


Figure 11 Undiscounted, cumulative cashflows for all 10 scenarios

5.2 Environmental impacts and costs

Figure 12 shows the carbon costs across all scenarios to 2038. Both scenarios 1 and 2 shown that gas boilers consistently have the highest climate change costs of all the heating options. The environmental NPC for scenario 1A and 2A are -£8,646 and -£7,744 respectively. Moreover, using the wood burners for 20% of space heating reduces CO_2e costs by 15% in Scenario 1 C&D and 17% in Scenario 2 C&D, with NPCs of -£7,345 and-£6,438 respectively. Using wood burners for 80% of space heating reduces these costs by 69% compared to the natural gas boiler options with NPCs of -£2,688 (1B) and -£2,369 (2B). The ASHP has the lowest carbon costs, with NPCs of -£835 (1E) and-£748 (2E) reducing emissions costs by 90% when compared to the gas boiler option, with costs falling through time as the power grid decarbonises. The ranked year 1 and year 15 carbon costs are shown in Table 10.

Table 10 Carbon costs in year 1 and year 15 for different heating system and occupancy patterns

Rank highest to lowest climate impact	Heating system/ pattern	Central carbon cost – year 1 and year 15			
		Scenario 1: Family of Four		Scenario 2: Older Couple	
		2023	2038	2023	2038
1 high	Gas Boiler only (A)	£655.07	£821.44	£586.73	£735.74
2	Wood burner 20% (C&D)	£556.53	£697.87	£487.79	£611.67
3	Wood burner 80% (B)	£203.69	£255.42	£179.52	£225.12
4 low	ASHP (E)	£116.66	£18.49	£104.49	£16.56

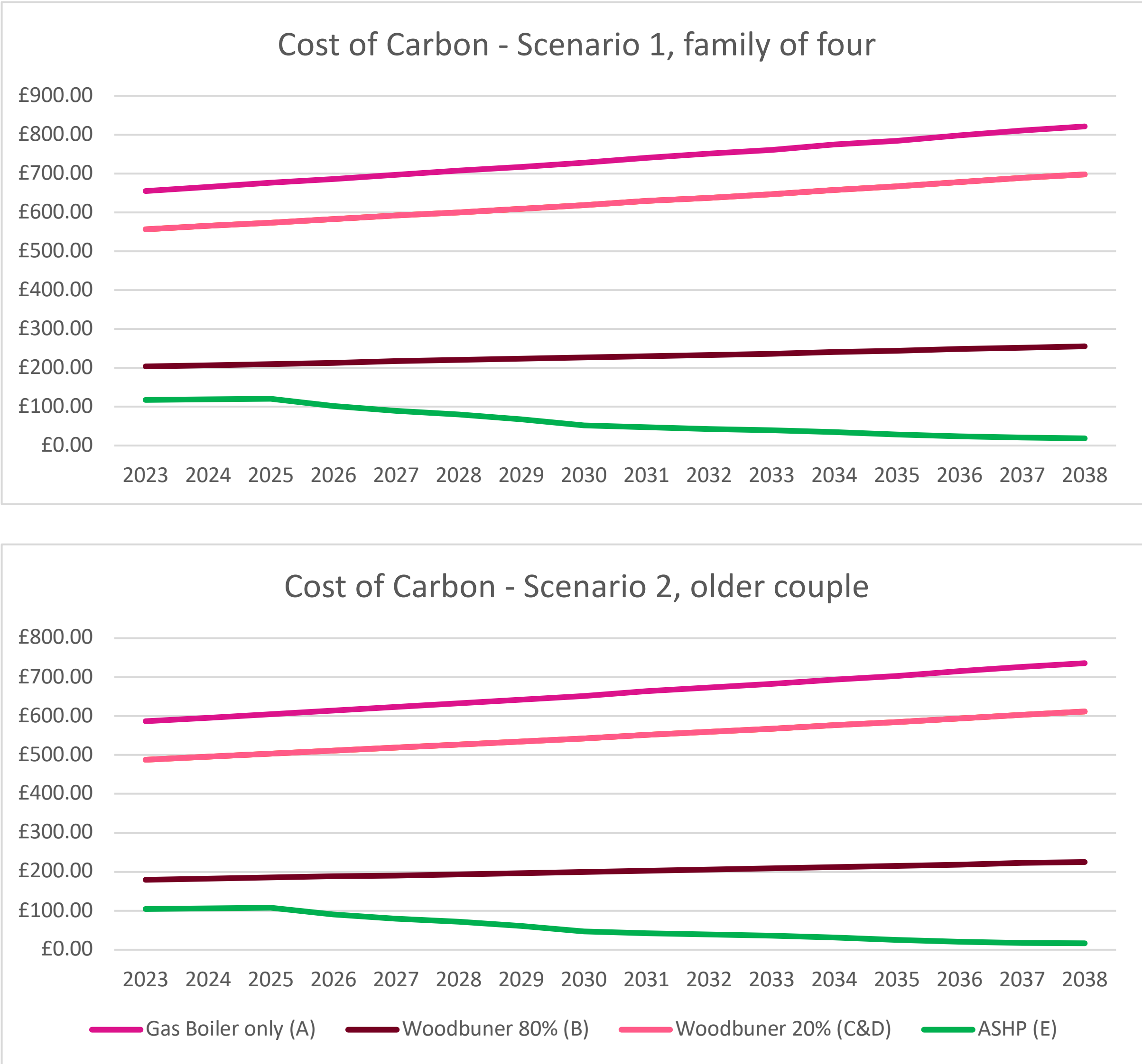
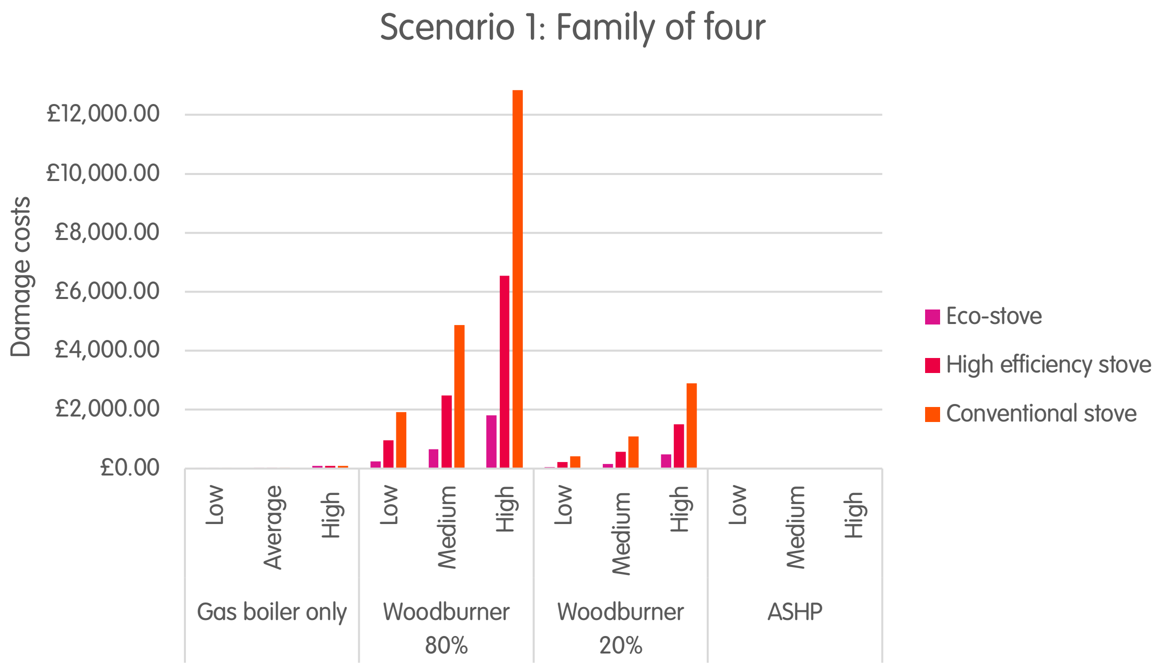


Figure 12 Carbon costs across all scenarios

5.3 Health impacts and costs

Figure 13 shows the air pollution damage costs across all scenarios and includes a range of stove types. The figure clearly shows that wood burners have much higher health costs than the other two heating system types. The figure shows a low, medium, and high impact scenario, based on the damage costs range as developed by DEFRA . The chart shows how the choice of stove type has a huge impact on the health impact costs. Indeed, the health costs are as high as £12,841 (1B) and £11,583 (2B) per year for the conventional stove with high emissions assumptions, while and eco stove with low emissions are as low as £250 (1B) and £225(2B). Assuming we adopt the medium pollution assumption and the mid-range high efficiency stove, the health NPCs for the 15-year life of the system are £364 (1A) and £326 (2A) for the gas boiler only, £9,060 (1B) and £8,171 (2B) for the 80% wood burner options, £2,262 (1C) and £2,388 (2C) for the 20% wood burner option. For the existing stove we assume the stove is a high efficiency model with higher associated particulate emissions and costs at -£7,632 (1D) and £7,623 (2D). Our model assumes the ASHPs produce no air pollution in operation and therefore have a health NPC of £0 (1&2E).



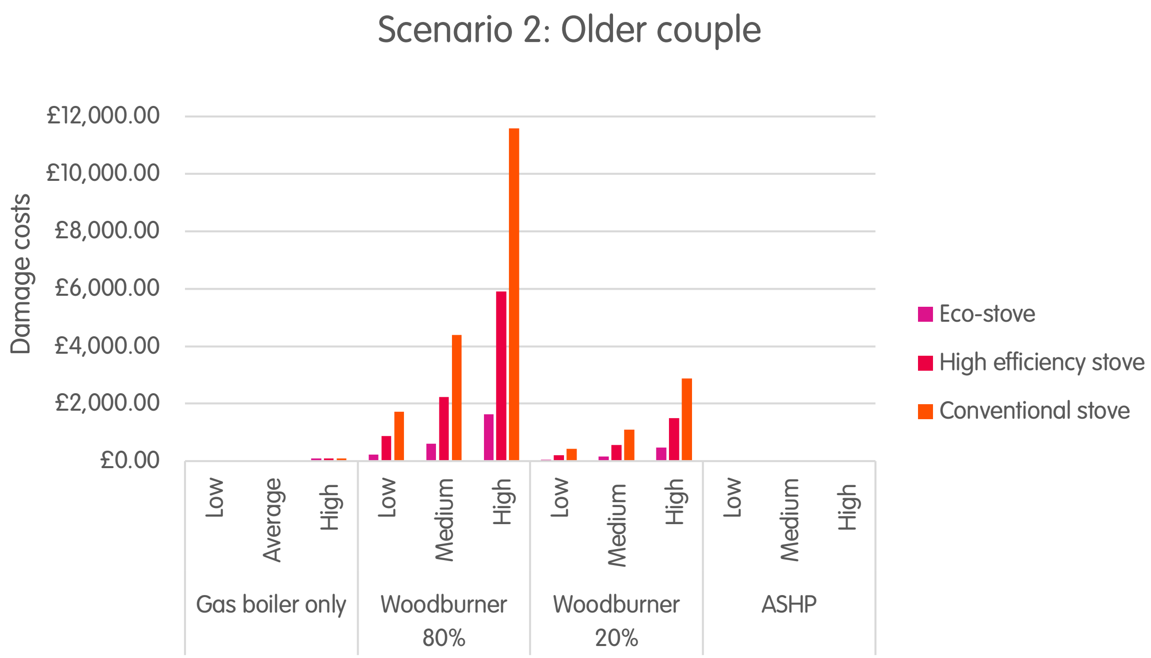


Figure 13 Year 1 health costs across all scenarios, separately for low, central, and high damage costs and different stove types.

Table 11 shows the different scenarios rank-ordered based on central damage costs which clearly indicates that the high wood burning scenarios perform the worst for conventional and high-efficiency stoves. All woodburning options are associated with higher damage costs than gas heating only or the ASHP.

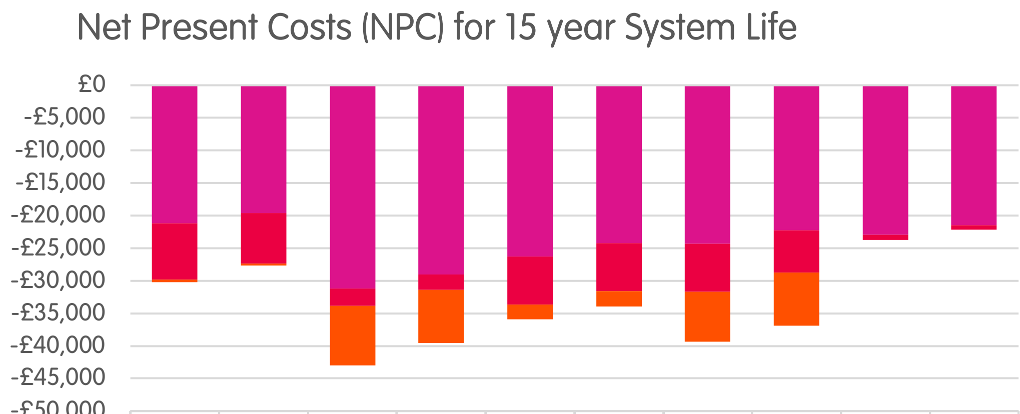
Table 11 Year 1 health costs across all scenarios, showing lowest to highest costs

Rank highest to lowest health impact	Heating system/ pattern	Annual central damage cost (low damage costs; high damage costs)	
		Family of four	Older couple
1 highest	Wood burner 80%, gas boiler 20% conventional stove	£4878.11	£4400.34
2	Wood burner 80%, gas boiler 20% high-efficiency stove	£2484.86	£2229.87
3	Wood burner 20%, gas boiler 80% conventional stove	£1085.47	£1087.41
4	Wood burner 80%, gas boiler 20% eco stove	£665.49	£600.17
5	Wood burner 20%, gas boiler 80% high-efficiency stove	£560.58	£559.98
6	Wood burner 20%, gas boiler 80% eco stove	£166.18	£163.96
7	Gas boiler 100%	£26.73	£23.94
8 lowest	ASHP 100%	0	0

Calculating estimates of air pollution damage costs for individual households is difficult for two main reasons. First, modelling pollution exposure for a household is complex and would rely on many assumptions; for example, around how often the stove would be restocked and occupancy of the room. For example, how often a stove is opened to be refuelled is highly predictive of resulting PM2.5 exposure (Chakraborty et al, 2020). Secondly, it would be hard to assign specific health effects to a certain indoor pollution level for one specific household, given that many other factors will play a role in determining actual health outcomes, such as existing health conditions (Jian et al., 2016). We have therefore not modelled these effects, but it should be noted that the health costs presented are therefore likely an underestimate.

5.4 Summary

In the total cost estimation, we combined the economic, environmental and health costs into a single NPC figure. Here we use the central fuel price NPC for all scenarios, and an environmental NPC using the same discount rate. For the health costs we use the medium pollution scenario. For the two new wood burner options (B & C) we assume the new stove is an eco-stove as these became mandatory for new installations from 1st January 2022. For the existing wood burner (Option D) we assume a high efficiency stove. This produces a combined cost for the 15-year life of the system shown in Table 12 and Figure 14. The table and figure clearly show that the wood burner options represent the highest cost option in all cases, with the high wood burner adoption scenario, the worst performing option. Although wood burners show an improvement in terms of the carbon emissions vs gas boilers, this is outweighed by the higher fuel costs. What is most striking is the high costs associated with air pollution from the wood burning stoves – obviously highest in the high adoption scenario – despite our optimistic assumptions on the stove type. Overall, the ASHP option shows the lowest lifecycle costs, with very low carbon emissions and no associated air pollution impacts.



	Option 1A	Option 2A	Option 1B	Option 2B	Option 1C	Option 2C	Option 1D	Option 2D	Option 1E	Option 2E
	Gas Boiler only		New Woodburner 80%		New Woodburner 20%		Existing Woodburner 20%		ASHP	
Health NPC	-£364	-£326	-£9,060	-£8,171	-£2,262	-£2,388	-£7,632	-£8,155	£0	£0
Environmental NPC	-£8,646	-£7,744	-£2,688	-£2,369	-£7,345	-£7,345	-£7,345	-£6,438	-£835	-£748
Economic NPC (central)	-£21,219	-£19,585	-£31,200	-£29,039	-£26,316	-£24,215	-£24,375	-£22,273	-£22,943	-£21,435

Figure 14 Combined economic, environmental and health costs across all scenarios over a 15-year lifespan

Table 12 Combined economic, environmental and health costs across all scenarios over a 15-year lifespan

NPC + environmental + health costs	Gas Boiler only		New Wood Burner 80%		New Wood Burner 20%		Existing Wood Burner 20%		ASHP	
	Option 1A	Option 2A	Option 1B	Option 2B	Option 1C	Option 2C	Option 1D	Option 2D	Option 1E	Option 2E
	£30,228	£27,654	£42,949	£39,579	£35,924	£33,040	£39,351	£36,866	£23,778	£22,183

6 Conclusions

This study aimed to investigate the relative cost of wood burners vs alternatives in the context of the current and future energy prices. To do this we undertook a dynamic simulation model of a 3-bedroom reference dwelling, with a higher occupancy Scenario 1 based on a family of four, and a lower occupancy Scenario 2 based on an older couple. We also modelled three different heating system types, a gas boiler only scenario, an ASHP and several wood burner adoption options. Using an in-depth literature review we then examined the economic, environmental and health impacts of these scenarios, including a sensitivity analysis of major sources of variability in these inputs. This has produced the following conclusions:

The chosen input assumptions are critical in determining the overall cost impact:

- The cost of wood fuel as an input is uncertain. Most wood fuel suppliers do not provide an exact weight at the point of sale, and this is further complicated by the species and moisture content. Moreover, we found very large variability in the purchase price for wood logs. In general wood purchased in bulk, online was significantly cheaper than wood bought in small quantities from non-specialist suppliers. Our research suggests that recent claims that wood burners are cheaper than natural gas heating, are based on £/kWh estimates at the very low end of this price range and are therefore highly optimistic.

- The environmental impact of wood fuel is also uncertain and is dependent on sustainably managed forestry. However, while lower carbon than gas boilers, wood fuel cannot be considered to be carbon neutral and heat pumps are likely to be a more sustainable choice over the long term.

- The health impacts and associated costs of wood burning stoves are very significant, although again subject to large ranges. Long-term exposure to air pollution contributes to chronic conditions, e.g., cardiovascular and respiratory diseases and lung cancer. Short-term exposure to high levels of air pollution is typically associated with acute health outcomes, such as exacerbation of asthma, increases in respiratory and cardiovascular hospital admissions and mortality. Moreover, well dried wood, burned in an eco-stove produces several orders of magnitude less air pollution than wet wood burned in an older stove.

We find little evidence that wood burners are a cheaper option, and in most cases are likely to be more expensive than the alternatives:

- Our modelling suggests the total cost of wood burners is likely to be more than a gas boiler or an ASHP, in most cases. In our central scenarios, the high wood burner adoption Option B, had an annual cost of ownership[21] of between £2,614-£2,433, around 47%-48% more than using an existing gas boiler (Option A) at £1,777-£1,641. The lower use wood burner scenario (Option C) had annual ownership costs of £2,204-£2,028, or 24% more than the gas boiler. Even where the wood burner was existing (Option D), annual ownership costs were £2,042-£1,866, still 15%-14% higher than gas. The ASHP (Option E) had annual costs of £1,922-£1,796, 8%-9% higher than the gas boiler.

- Only where a large majority of the wood fuel can be provided for free, are wood burners likely save households money. Moreover, unless wood is purchased in bulk from specialist suppliers, these costs may be substantially higher, with some sources of wood fuel (i.e., from garages) almost four times more expensive than gas.

- Wood burners are likely to produce lower carbon emissions than gas boilers, with our study showing a 69% reduction in carbon costs in the high adoption scenario, although our modelling shows that ASHPs are likely to have the lowest carbon costs (90% less than gas boilers).

- Wood burners are likely to create very significant air pollution impacts, in particular eventual mortality through long-term exposure to PM and increase in asthma incidence particularly in children. In our high wood burner adoption scenario, these public health costs were £9,060 (Option 1) and £8,171 (Option 2) over a 15-year period. If we assume the worst-case use of damp wood in an older stove (Option D) these costs rise to £39,243 (Scenario 1) and £39,106 (Scenario 2) respectively.

- In our central scenario, we found the total cost impact of wood burners to be substantially higher than either the gas boiler or ASHP. The with the high adoption Option B costing 42%-43% more than a gas boiler, with the lower use Option C costs being 19% higher, or 30%-33% higher if the wood burner was an older model (Option D), despite the installation savings.

- By contrast we found that when factoring economic, environmental and health impact costs, the ASHP was only 79%-80% of the total cost of the gas boiler.

[21] The equivalent annual cost (EAC) is the annual cost of owning, operating, and maintaining an asset over what we assume is a 15-year life.

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Appendix 1 DesignBuilder modelling input assumptions

		Heating setpoint temperature	Heating period	Gas boiler Option A	New Woood burner (primary), Gas boiler (secondary) Option B	Gas boiler (primary), New Wood burner (secondary) Option C	Gas boiler (primary), Existing Wood burner (secondary) Option D	Air Source Heat Pump (ASHP) Option E
Scenario 1 - Family of Four	Bed1 + Bed2	18C	00:00-9:00	gas boiler 85% efficiency + radiators	gas boiler 85% efficiency + radiators	gas boiler 85% efficiency + radiators	gas boiler 85% efficiency + radiators	ASHP with SCoP of 3.5
	Bed3	18C	00:00-9:00	gas boiler 85% efficiency + radiators	wood burner, 82.5% efficiency	gas boiler 85% efficiency + radiators	gas boiler 85% efficiency + radiators	ASHP with SCoP of 3.5
	Kitchen	18C	5:00-10:00 and 17:00-23:00	gas boiler 85% efficiency + radiators	wood burner, 82.5% efficiency	gas boiler 85% efficiency + radiators	gas boiler 85% efficiency + radiators	ASHP with SCoP of 3.5
	Living	21C	14:00-23:00	gas boiler 85% efficiency + radiators	wood burner, 82.5% efficiency	gas boiler 85% efficiency + radiators	gas boiler 85% efficiency + radiators	ASHP with SCoP of 3.5
	Lounge	22C	9:00-23:00	gas boiler 85% efficiency + radiators	wood burner, 82.5% efficiency	wood burner, 82.5% efficiency	wood burner, 82.5% efficiency	ASHP with SCoP of 3.5
	Bathrooms	21C	5:00-10:00 and 17:00-23:00	gas boiler 85% efficiency + radiators	wood burner, 82.5% efficiency	gas boiler 85% efficiency + radiators	gas boiler 85% efficiency + radiators	ASHP with SCoP of 3.5
Scenario 2 -		**Heating setpoint temperature**	**Heating period**	**Option A**	**Option B**	**Option C**	**Option D**	**Option E**

Older Couple	Main bedroom	18C	00:00-9:00	gas boiler 85% efficiency + radiators	wood burner, 82.5% efficiency	gas boiler 85% efficiency + radiators	gas boiler 85% efficiency + radiators	ASHP with SCoP of 3.5
	other bedrooms	12C	00:00-24:00	gas boiler 85% efficiency + radiators	wood burner, 82.5% efficiency	gas boiler 85% efficiency + radiators	gas boiler 85% efficiency + radiators	ASHP with SCoP of 3.5
	Kitchen	18C	5:00-10:00 and 17:00-23:00	gas boiler 85% efficiency + radiators	wood burner, 82.5% efficiency	gas boiler 85% efficiency + radiators	gas boiler 85% efficiency + radiators	ASHP with SCoP of 3.5
	Living	21C	14:00-23:00	gas boiler 85% efficiency + radiators	wood burner, 82.5% efficiency	gas boiler 85% efficiency + radiators	gas boiler 85% efficiency + radiators	ASHP with SCoP of 3.5
	Lounge	22C	9:00-23:00	gas boiler 85% efficiency + radiators	gas boiler 85% efficiency + radiators	wood burner, 82.5% efficiency	wood burner, 82.5% efficiency	ASHP with SCoP of 3.5
	Bathrooms	21C	5:00-10:00 and 17:00-23:00	gas boiler 85% efficiency + radiators	wood burner, 82.5% efficiency	gas boiler 85% efficiency + radiators	gas boiler 85% efficiency + radiators	ASHP with SCoP of 3.5

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