Relight my fire or scatter the ashes? The economic and health costs of woodburning stoves

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Abstract
Recent winters have seen a huge increase in energy prices, prompting a renewed interest in woodburning stoves as an alternative and presumably cheaper form of heating. However, domestic combustion – including wood burning – is the biggest source of fine particulate matter (PM 2.5) in cities like London. Wood is classified as a renewable energy source; however, this is only appropriate with strict forest management techniques.

Here, we report the results of a study done together with the environmental charity "Global Action Plan" and the not-for-profit organization "Impact on Urban Health". We undertook energy simulation modelling of a typical 3-bedroom London mid-terraced house. We assumed two occupancy scenarios, a higher occupancy scenario based on a family of four, and a lower occupancy scenario based on a retired couple with no children at home. We modelled five different heating system options: (A) Existing gas boiler providing 100 % of heat. (B) Newly 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. Analysis showed that gas boilers and heat pumps are cheaper options for home heating than the wood burner options in either scenario. Only for those who can largely source their own wood for free, woodturners might become cost competitive. The public health costs of wood burning are substantial, in the long-term contributing to chronic health conditions, e.g., cardiovascular, and respiratory diseases, and in short-term to acute health outcomes, such as exacerbation of asthma.

Hence, we argue that burners are not a cost-effective, healthy or sustainable alternative to other forms of heating, notably heat pumps, and should not play a critical role in the transition to net-zero.

Introduction
Wood is considered a form of renewable energy (Directive 2009/28/EC) and comes often with the notion of being clean and green energy. The use of wood burners has been increasing in developed countries over the last decades and has seen a particular in interest in the last couple of winters when energy prices soared. 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). Data suggest a 40 % increase in market share since the energy price crisis. In this paper, we present the outcomes of a simulation study that tries to understand the true costs of woodburning, both in terms of money spent for heating but also health effects due to pollution resulting from burning wood. We have designed two occupancy scenarios with five heating options, including woodstoves, gas boilers and heat pumps. Wood can be burned in multiple ways, i.e. highly processed wood pellets, less processed wood chips and wood logs. In this work, we focus on wood logs only.

ECONOMIC ASPECTS OF WOODBURNING

Commodities such as oil and natural gas (and, to a lesser extent, coal) are actively traded on the global market, featuring daily published reference prices, comparable units, extensive historical records, and readily available future projections. In contrast, wood fuel prices are significantly influenced by local factors, relying on factors such as scale, transportation, and adopted storage methods. The limited existing academic literature on the subject underscores the multitude of factors contributing to the substantial variability in biomass prices.

Akhtari et al. (2014) emphasize the impact of different supply chain types on cost variation, highlighting transportation costs as the most significant factor. According to Jeswani et al. (2019), biomass boilers with the now-retired Renewable Heat Incentive (RHI) subsidy were 52 % more cost-effective than gas boilers, but without the subsidy, they become 23 % more expensive. Jablonski et al. (2008) outline potential future scenarios for the demand for bio-heat in the UK residential sector, projecting estimates ranging from 3 % (conservative estimate) to 31 % (optimistic estimate) of the total energy consumed in the heat market. Furthermore, economic theory suggests that with a substantial increase in demand, wood fuel prices may continue their recent upward trend, particularly in situations of constrained supply (Labandera et al., 2017).

GREENHOUSE GAS EMISSIONS

Numerous national and international policy frameworks, including those in the UK and the EU, categorize wood fuel as zero-carbon at the point of combustion. This classification deems wood as a renewable energy source, making it eligible for financial or regulatory support similar to other renewable energy sources. This categorization is based on the assumption that the CO_2 emissions released during wood combustion are eventually sequestered back into growing trees. However, criticisms exist regarding the presumption of carbon neutrality. One concern is the time delay between CO_2 emissions from burning wood and the subsequent carbon sequestration into growing biomass. During this interval, CO_2 molecules remain in the atmosphere, contributing to global warming (Cherubini et al., 2011).

Another critique involves the oversight of potential foregone sequestration. Without harvesting, forests and soils absorb more CO_2, preventing it from entering the atmosphere and causing global warming (Helin et al., 2016). Although forest harvesting might enhance the surface albedo, reflecting more sunlight and cooling the climate, this effect is outweighed by the warming impact of black carbon – tiny particles that absorb sunlight. This warming effect is particularly notable in snowy areas, resulting in an overall warming potential attributed to wood burning (Arvesen et al., 2018). A study conducted in Australia indicated that emissions from wood heating have a greater climate impact than those from gas heating or reverse cycle air conditioning (Robinson, 2011).Waste wood is less concerning 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 in particular CO_2. 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 from the Standard Assessment Procedure (SAP) as used by the UK government (BEIS, 2022).

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). 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). 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 N_2O, domestic combustion only plays a subordinate role; for sulphur dioxide (SO2) 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 also 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.

HEALTH IMPACTS

According to the World Health Organization, approximately 7 million premature deaths occur annually due to air pollution. In the UK, estimates suggest that between 2017 and 2025, the costs to the NHS and the social care system associated with fine particulate matter and nitrogen dioxide amount to around £1.6 billion (OHID, 2022). Air pollution modelling predicts the onset of 2.4 million new cases of disease in England from 2019 to 2035. Among these, PM 2.5 is expected to cause 350,000 cases of coronary heart disease and 44,000 cases of lung cancer in England (DEFRA, 2019). The long-term exposure to air pollution is linked to chronic conditions, including cardiovascular and respiratory diseases, as well as lung cancer. Short-term exposure to elevated air pollution levels is typically associated with acute health outcomes, such as exacerbation of asthma, increased hospital admissions for respiratory and cardiovascular issues, and mortality. Vulnerable populations, such as young children, the elderly, and individuals with respiratory conditions like asthma, are particularly susceptible (Chakraborty et al., 2020). The following health effects in Table 1 are linked to air pollution (Blake & Wentworth, 2023).

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 emission or kWh energy used (DEFRA, 2023a). These are generally conservative estimates and only included directly attributable health impacts. 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.

Methods

In this study we aimed to examine the impact of these different factors on the economic, social and environmental cost of woodburning for a typical urban family home, compared to other heating technologies.

CHOSEN SCENARIOS

Dwelling characteristics

Given that wood burning is particular problematic in cities such as London, and with around 32 % of London's homes built before 1919, we opted for a typical 3-bedroom mid-terrace late Victorian dwelling. The building of approximately 136 m2 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 (see Table 2). However, we assume that the solid walls and floors remain uninsulated.

Occupancy and heating schedules

We modelled two occupancy scenarios. *Scenario 1* consisted of a 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 7–9 AM and 6–9 PM) and to dry laundry/towels. *Scenario 2* consisted of an 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 (9 AM–5 PM) and in the bathroom and

Table 1. Acute and chronic health 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

Table 2 Reference dwelling thermal parameters.

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, 300 mm 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

bedroom as well first thing in the morning and in the evening (typically 7–9 AM and 6–9 PM). Couple have a tumble drier. We crated five different heating modes, see Table 3.

COST ESTIMATES

Gas and 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 2023 price cap predictions, and personal correspondence with Cornwall Insight. The UK government 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 expected prices to fall by the end of 2023 before a return to the background price inflation trend of 3 % for energy bills (see Figure 1).

Wood 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. We did 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, including both online and in person research at various locations around southeast London, on the 16th of February 2023. The results from 14 sources 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. Around 19 % of users buy wood from general, non-specialist suppliers

Table 3. The five heating options.

Option	Label	Description
A	100 % natural gas boiler	An existing condensing gas boiler provides all the homes heating and hot water
B	Two new woodburners(80 %) with natural gas for secondary heating (20 %)	Two new woodburning stoves are installed which are used to provide 80 % the homes space heating. The gas boiler is used for 20 % of heating needs to heat peripheral rooms and for hot water.
C	Existing natural gas (80 %) with one new wood burner as secondary heating (20 %)	Only one woodburning stove is installed which provides 20 % of heat demand to the 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 (80 %) with existing wood burner as secondary heating (20 %)	Same as Option C except but wood burner is pre-existing.
E	New Air Source Heat Pump (ASHP) providing 100 % of heat	Involves the installation of an ASHP with new cylinder, radiators, and controls. System provides all heating and hot water for the home.

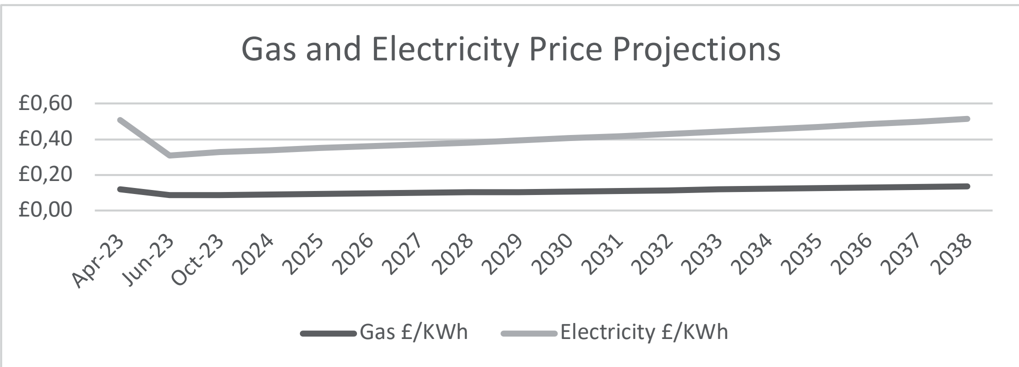


Figure 1. Gas and electricity prices for the modelling period.

Table 4. 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 %

(garages & garden centres etc.) while 31 % comes from specialist suppliers and the rest from a range sources. Based on these information, we constructed low, medium, and high wood fuel price scenarios, based on the values from our market research and their relative market share (Table 4).

Capital and operational expenditure

To model the net present cost of the various system configurations we must first include the capital cost of the various system options (CAPEX) and then there operating costs (OPEX). Table 5 shows the assumptions made. All prices were adjusted a 2 % inflation rate.

AIR POLLUTION AND HEALTH IMPACTS

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, NO_x and SO_x. Gas boilers have generally lower emission rates than wood stoves. The type of wood stove used is hugely important especially regarding particulate emissions. The 95 % confidence intervals around the mean are very large, i.e. for any particular stove use, emissions could be much higher. For modelling purposes, we are using the mean estimates, but actual emissions could be much higher depending on the burning practices and wood moisture content.

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). 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.

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 Emissions of kg CO_2e per kWh as follows for the sources of energy modelled here: Electricity heating season: 0.154; mains gas 0.21; wood logs 0.028.

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 historically used refrigerants, hydrofluorocarbons (HFCs) that are potent greenhouse gases with a global warming potential of over 1,000 times that, of CO_2. Leakages might occur in 35 % of domestic installations; however, modern heat pumps use refrigerants with less global warming potential (DECC, 2014; Singh Gaur et al., 2020). As an example, the refrigerant R410A had a global warming potential of 2088, whereas R454B only 466 (Bobbo et al., 2019) and R1234ze(Z) of < 1 (Kosmadakis et al., 2020). For our modelling we assumed that no leakages occur.

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

Table 5. CAPEX and OPEX for the five heating regimes.

Option	CAPEX	CAPEX Notes	OPEX	OPEX Notes
A	£2,900	Gas boiler is replaced in year 8, with £2,500 cost.	£4,150	Annual boiler service and cover starting at £240/year.
B	£5,900	2 wood burners installed, £1,500 each. Gas boiler is replaced in year 8, £2,500.	£6,744	2X annual chimney sweep at £150. Annual boiler service and cover starting at £240/year.
C	£4,900	1 new wood burner is installed, £2,000. Gas boiler is replaced in year 8, £2,500.	£5,447	Annual boiler service and cover starting at £240/year. 1X Annual chimney sweep at £75.
D	£2,900	Gas boiler is replaced in year 8, £2,500.	£5,447	Annual boiler service and cover starting at £240/year. 1X Annual chimney sweep at £75.
E	£8,000	ASHP System install, £13,000 including new radiators. Minus £5,000 Boiler Upgrade Scheme grant.	£925	An annual service for the 15-year life of the ASHP at £163. £0.3/day saving from gas standing charge disconnection.

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. 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.

SOFTWARE AND ANALYSIS

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 a 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 cover; overshading by surrounding buildings; occupancy patterns; lighting; internal heat gains from equipment; and ventilation. The combination of these occupancy scenarios and heating system options produces a total of 10 different scenarios.

Results

The heat energy demand profiles for each of the 10 options – two occupancy scenarios and five heating options – is shown in Figure 2. 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 (Terry & Galvin, 2023).

Heat and water energy demand is 10 % lower in Scenario 2, where fewer rooms are heated.

COST-BENEFIT ANALYSIS

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.

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. These data were then combined with the CAPEX and OPEX assumptions from Table 5.

Figure 3 shows the central 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). This is closely followed by the ASHP system (Options 1E & 2E). The third cheapest system configuration is where the existing wood burner is providing second-

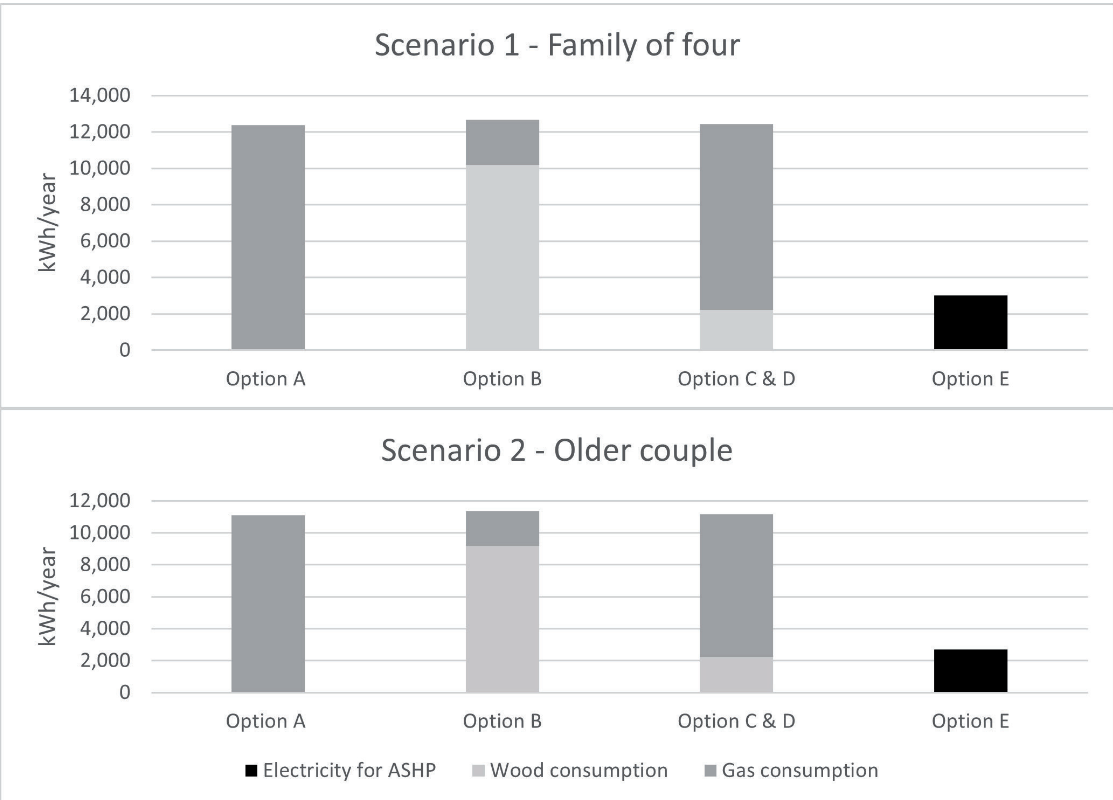
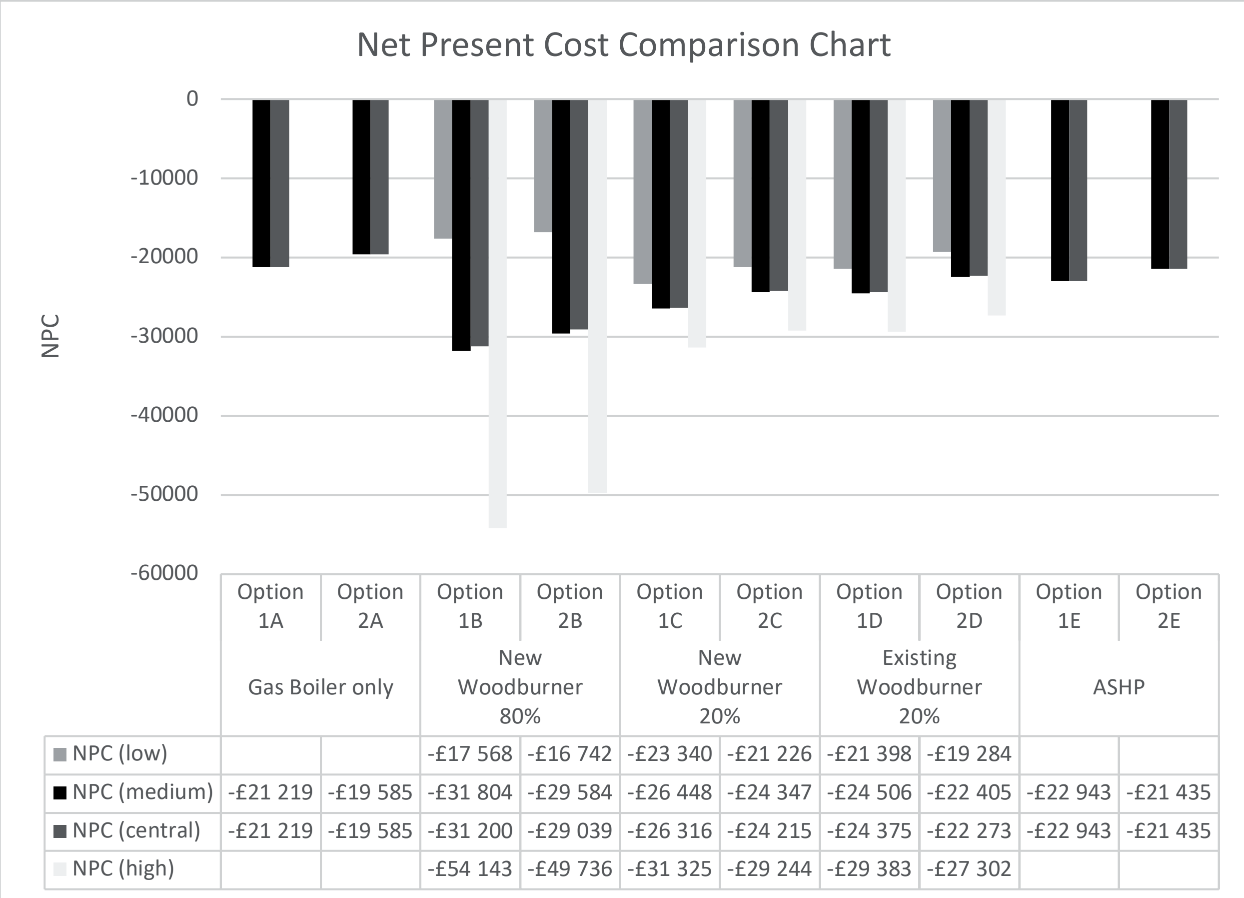


Figure 2. Energy outputs across all scenarios.

ary heating (Options 1D & 2D). In the central scenario, the two new wood burner options are the most expensive (Option 1C), with the dual wood burner dominant system (Options 1B & 2B). 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) with 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 % and 15 %, cheaper than the next cheapest gas boiler only configuration.

Figure 4 shows the annualised costs of the central scenarios.



	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)			-£17 568	-£16 742	-£23 340	-£21 226	-£21 398	-£19 284		
NPC (medium)	-£21 219	-£19 585	-£31 804	-£29 584	-£26 448	-£24 347	-£24 506	-£22 405	-£22 943	-£21 435
NPC (central)	-£21 219	-£19 585	-£31 200	-£29 039	-£26 316	-£24 215	-£24 375	-£22 273	-£22 943	-£21 435
NPC (high)			-£54 143	-£49 736	-£31 325	-£29 244	-£29 383	-£27 302		

Figure 3. Net Present Cost (Economic) comparison across all system types, scenarios and fuel price assumptions.

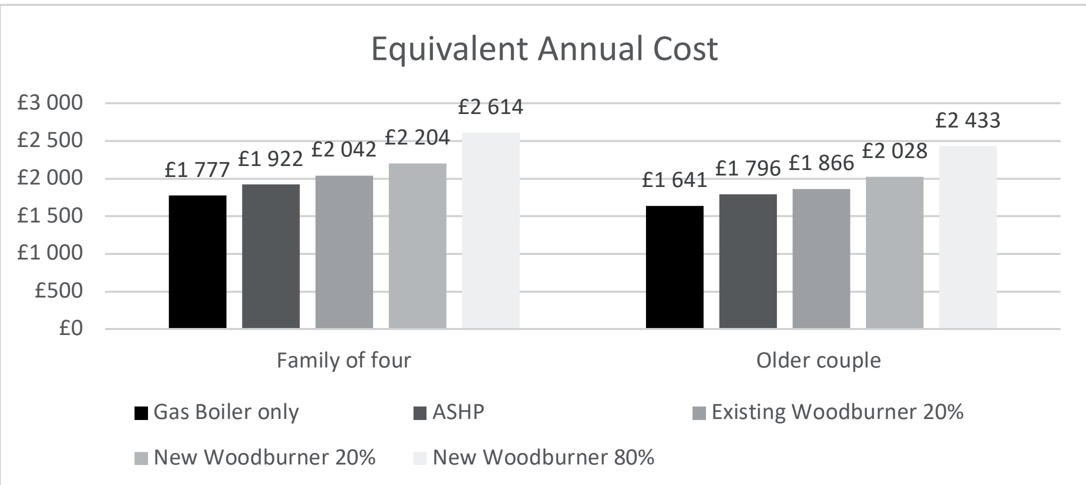


Figure 4. Equivalent Annualised Costs across all options.

Environmental impacts and costs

Both scenarios 1 and 2 show that gas boilers consistently have the highest climate change costs of all the heating options (see Table 6). 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.

Health impacts and costs

Table 7 summaries 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 choice of stove type has a huge impact on the health impact costs.

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.

Figure 5 clearly shows 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.

Table 6. 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

Table 7. Year 1 health costs across all scenarios, showing lowest to highest costs.

Rank	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 (£1913.1; 12841.35)	£4400.34 (£1725.77; 11583.44)
2	Wood burner 80 %, gas boiler 20 % high-efficiency stove	£2484.86 (£962.72; £6544.07)	£2229.87 (£868.43; £5902.71)
3	Wood burner 20 %, gas boiler 80 % conventional stove	£1085.47 (£421.34; £2882.61)	£1087.41 (£422.56; £2872.51)
4	Wood burner 80 %, gas boiler 20 % eco stove	£665.49 (£249.98; £1811.13)	£600.17 (£225.47; £1633.16)
5	Wood burner 20 %, gas boiler 80 % high-efficiency stove	£560.58 (£213.86; £1507.83)	£559.98 (£214.23; £1503.03)
6	Wood burner 20 %, gas boiler 80 % eco stove	£166.18 (£58.26; £474.56)	£163.96 (£57.99; £465.53)
7	Gas boiler 100 %	£26.73 (£4.71; £101.28)	£23.94 (£4.22; £90.71)
8 lowest	ASHP 100 %	0	0

Discussion & conclusion

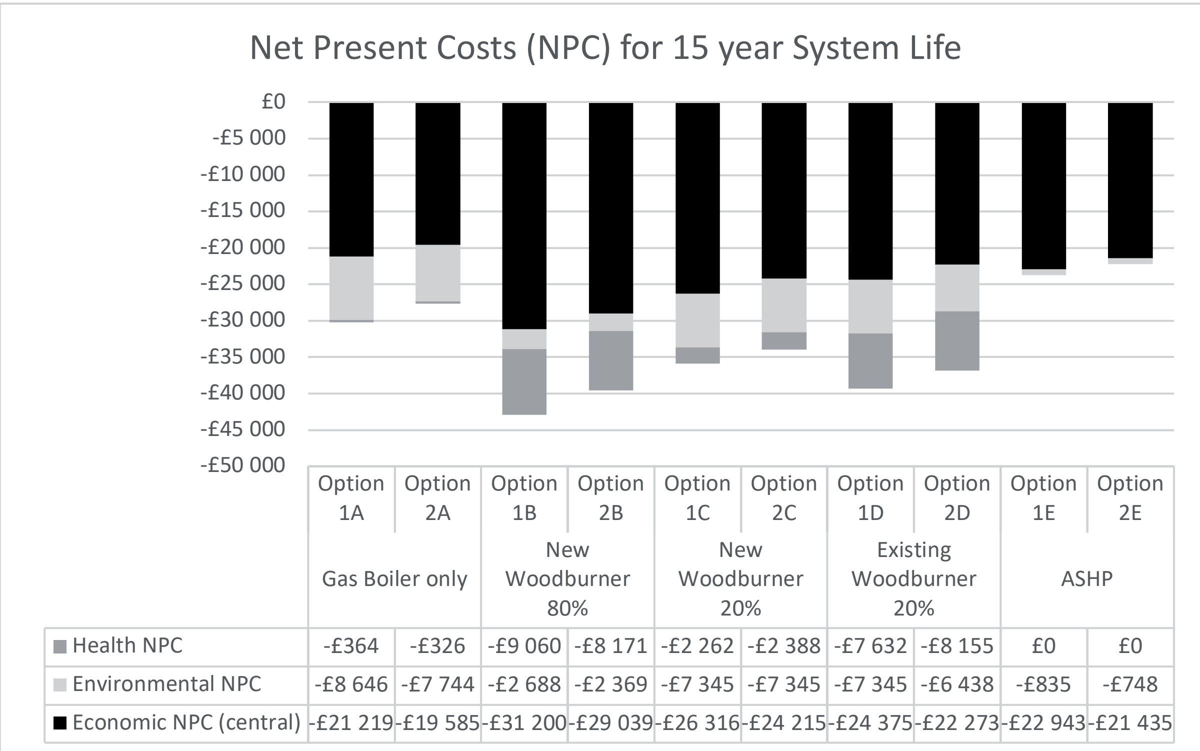
This study aimed to investigate the relative cost of wood burners vs alternatives for home heating in the context of the current and future energy prices. To do this we undertook a dynamic simulation model of a 3-bedroom reference dwelling, with a higher occupancy Scenario 1 based on a family of four, 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. Based on a 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.

Our study reveals the uncertainty surrounding the cost of wood fuel as an input. The majority of wood fuel suppliers do not specify an exact weight at the point of sale, and this uncertainty is compounded by factors such as species and moisture content. Additionally, we observed substantial variability in the purchase price of wood logs. Generally, wood purchased in bulk online proved to be significantly more cost-effective compared to smaller quantities obtained from non-specialist suppliers. Our research indicates that recent assertions claiming the cost-effectiveness of wood burners in comparison to natural gas heating are based on £/kWh estimates at the lower end of the price spectrum, making them overly optimistic.

The environmental impact of wood fuel remains uncertain and relies on sustainably managed forestry practices. Despite being lower in carbon emissions compared to gas boilers, wood fuel cannot be deemed carbon neutral, and heat pumps are likely to represent a more sustainable choice in the long run. Our modelling indicates that wood burners are likely to yield reduced carbon emissions compared to gas boilers, with a 69 % decrease in carbon costs in the high adoption scenario. However, Air Source Heat Pumps (ASHPs) are anticipated to have the lowest carbon costs. Given the questionable classification of wood as a renewable energy source and considering the significant health impacts and associated costs of wood burning stoves, it suggests that wood stoves should not play a prominent role in the transition to a net-zero environment. This is particularly crucial because long-term exposure to air pollution contributes to chronic conditions such as cardiovascular and respiratory diseases, as well as lung cancer. Short-term exposure to elevated air pollution levels is typically linked to acute health outcomes, including asthma exacerbation, increased respiratory and cardiovascular hospital admissions, and mortality.

Our modelling suggests the total cost of wood burners is likely to be more than a gas boiler or an ASHP, in most cases. 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, costs may be substantially higher, with some sources of wood fuel almost four times more expensive than gas.

In order to conduct a manageable modelling study, we had to simplify some assumptions, such as on future CO_2e intensity of wood which will reduce slightly with transport becoming decarbonized. We provided justifications for such simplifications. Also, we only modelled two occupancy scenarios in one reference dwelling in order to provide relatable examples; however, our calculations are hence not representative for the building stock. There are also significant uncertainties e.g. around wood prices.



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

Hence, in summary, wood burning stoves should not play a major role in the transition to net-zero with heat pumps overall being the least polluting choice with lower emissions. The public discourse around wood burners must focus more on the negative health impacts but also the higher costs.

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