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Evaluating heat pump retrofit strategies for a typical domestic building in the UK

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Abstract

In 2022, domestic buildings accounted for 20% of the United Kingdom's greenhouse gas emissions, largely driven by the combustion of gas and oil for space heating and hot water. Given the sector's high dependence on fossil fuels, decarbonization is critical to achieving the UK's 2050 Net Zero target. The adoption of heat pumps offers a particularly promising pathway, providing an efficient and low-carbon alternative to conventional gas boilers.
AWHP systems typically operate at lower supply temperatures compared to conventional gas boilers, which necessitates modifications to the design and/or operation of existing heating systems. A key change involves upgrading the radiators to low-temperature ones to compensate for the lower supply temperature. However, extending the duration of heating schedule as an alternative approach may also be effective and could mitigate the need for radiator replacement. In this study, these two retrofit strategies are examined for a typical UK domestic building from the technical and economic aspects by developing a dynamic thermal model of a building, heated separately by an AWHP and by a gas boiler. The simulation results for the defined case studies were evaluated using key performance indicators (KPIs), including Annualized Net Present Value (ANPV), upfront cost, running cost, final energy demand, and the system's ability to maintain indoor temperature within the comfort range. By using these KPIs and comparing these case studies, the research aims to identify the most cost-effective strategy to overcome the retrofit challenges associated with heat pump adoption in existing domestic buildings in the UK. The findings indicate that, under an appropriate operational strategy, an AWHP can supply a thermal comfort level equal to or higher than those of a gas boiler. Additionally, extending the heating duration, instead of upgrading the radiators, can provide similar or improved comfort in buildings while reducing overall costs.

Keywords: Air-to-water heat pumps; heat pump retrofit strategy; Space heating; Radiator sizing; Econocmic and technical assesment; Decarbonization.

1. Introduction

The impacts of climate change are becoming increasingly evident both globally and, in the UK, [1], underscoring the need to reduce greenhouse gas (GHG) emissions. The UK, as one of the major economies, has set a target to achieve net zero emissions by 2050 [2]. Meeting this commitment requires progress across all major sectors, including heating and cooling in domestic buildings, which make a significant contribution to national emissions. The building sector remains a significant emitter because heating is still largely fossil-fuelled. In 2022, domestic buildings accounted for about 20% of UK greenhouse-gas emissions, driven mainly by the combustion of gas and oil for space and water heating. According to the 2021 Census, 73% of households relied on mains gas as their sole source of central heating, 8% used electric systems, 5% used oil, and 2% had no central heating [3]. Low-carbon heating in domestic buildings is therefore central to UK climate policy. Heat pumps can reduce reliance on gas and other fossil fuels in domestic buildings and support the electrification of heat. Air-source, ground-source, and water-source systems can meet a large share of heating

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demand. Given that most UK homes use radiators, air-to-water heat pumps (AWHPs) are perceived to be a suitable option for conventional gas boilers.

If the deployment of heat pumps is effectively implemented and supported through adequate infrastructure, financial incentives, and public engagement, AWHPs can make a substantial contribution to decarbonization and long-term climate resilience [4], [5], [6], [7]. However, only about 1% of UK homes currently use a heat pump—one of the lowest adoption rates in Europe [8]. This figure contrasts with the national target to increase installations from 55,000 units per year in 2021 to 600,000 per year by 2028 [9]. A major barrier in decarbonizing residential heating is the overall readiness of the housing stock. According to Lamb et al. [10], only about 11% of UK dwellings are heat-pump-ready without substantial upgrades to insulation, radiators, or control systems, which indicates the scale of retrofit required across UK homes. Alongside feasibility studies, factors shaping efficiency and comfort in retrofitted homes have been examined in articles. For example, research by Lindhe et al. [11] reports that undertaking retrofits in domestic buildings without adequate fabric improvements can increase the risk of over-sizing and inefficient operation of installed systems. Article [12] emphasizes the need for appropriate design adjustments in heat-pump retrofits and outlines that proceeding without attention to design can harm both technical outcomes and user satisfaction. The effect of parameters such as location and supply temperature on performance of heat pump was also investigated by Abid et al. [13], showing that control strategies have a significant influence on energy consumption, costs, and emissions.

The economics of deploying heat pumps in domestic buildings is another area of focus. Schreurs et al. [14] use indicators such as Net Present Value (NPV) and Internal Rate of Return (IRR) to assess the techno-economic viability of pairing heat pumps with solar PV. Report from Element Energy and the Energy Systems Catapult [15] shows that heat pumps can deliver long-term cost savings, but high upfront costs and uncertainties around operational performance remain barriers to faster adoption, particularly under dynamic tariffs. This concern is also present in the study by Qayyum et al. [16] similarly evaluated a heat pump as an alternative to a gas boiler in a well-insulated four-bedroom semi-detached house with four occupants, finding that while CO_2 emissions were reduced by 40%, the running costs were 91% higher than those of a gas boiler.

Despite the growing research in this field, further research is needed to determine how AWHPs can be operated most cost-effectively in UK domestic buildings. This study focuses on practical strategies for heat pump operation through the evaluation of both the technical feasibility and economic performance of AWHPs, based on simulations of domestic building's thermal behavior.

This study aims to explore how suitable AWHPs are as a low-carbon alternative to gas boilers in UK homes, looking at both technical performance and cost-effectiveness. To support the economic analysis, the thermal behavior of typical domestic building was simulated using TRNSYS, a widely used building energy modelling tool. By introducing key indicators (KPIs) such as the Annualized Net Present Value (ANPV), the study highlights how economically viable AWHPs can be. It also examines different ways of operating AWHP systems to find the most efficient and cost-effective operation pattern that can deliver reliable thermal comfort.

2. Method

A model of a typical domestic building was developed in TRNSYS, as described in Section 2.1. This model was integrated separately with a gas boiler and an AWHP to compare their performance. The characteristics of each system are detailed in Section 2.2, and the validation process is presented in Section 2.4.The model was then used to simulate the thermal behavior of the domestic building under five case studies, described in Section 2.3. The simulation results were used to perform a techno-economic analysis based on five key performance indicators, discussed in Section 2.5. Section 3 presents the results of this analysis, which were used to evaluate the suitability of heat pump adoption and to determine the most cost-effective operating strategy for AWHPs. The overall methodology of the present research is summarized in Fig 1.

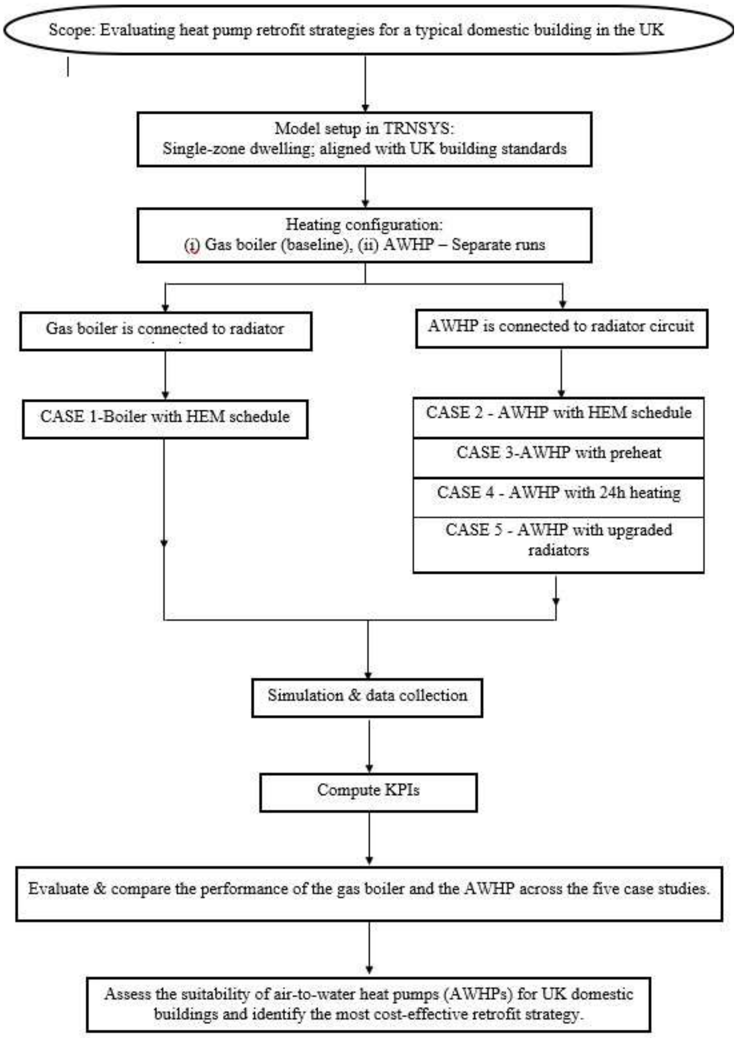


Figure 1. Flowchart of the study on heat pump retrofit strategies for a typical domestic building in UK.

2.1. Building description

Fig. 2 illustrates the domestic building model used in the simulation. The TRNSYS Type 56 component was employed to represent a single-zone building. The characteristics of the building were defined using TRNBuild, an interface of TRNSYS.

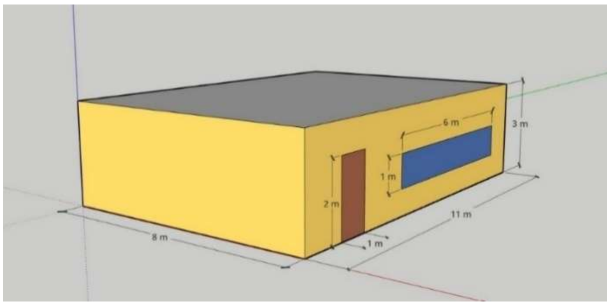


Figure 2. Single-zone model of a building developed in TRNBuild

The building has a floor area of 88 m^2 and a volume of 264 m^3. The envelope comprises four external walls, a window, a door, and a roof exposed to outdoor air, and a floor in contact with the ground. The layers and construction materials of all elements were defined in line with UK building regulations [17]. Table 1 shows the list of U-value for different parts of building model. The weather data of Cardiff was used as the environmental condition for the simulations and outdoor temperature profile was generated by the TRNSYS component Type 15. The ground temperature (T_g) was taken as 8 °C and held constant over the simulation. To simplify the model, the effects of shading, solar radiation, internal gains from occupants and electrical equipment, as well as infiltration and ventilation were neglected.

Table 1. List of U-values of different parts of single-zone building.

Building parts	U-value (W/m^{2}K)
External walls	0.3
Roof	0.25
Floor	0.25
Window	1.1
Door	1

The total fabric heat loss ($Q_{f,l}$) is given by:

$$Q_{f,l} = \sum_{i=1}^{n} U_i \, A_i (T_{ind} - T_{out}) \tag{1}$$

In above equation, U_i and A_i are the thermal transmittance and surface area of the i^{th} building element, respectively, T_{ind} is the indoor air temperature, and T_{out} is the outdoor air temperature. In this model, ventilation heat loss was neglected. Therefore, the total heat loss of the building ($Q_{total,l}$) is calculated by:

$$Q_{total,l} = Q_{f,l} \tag{2}$$

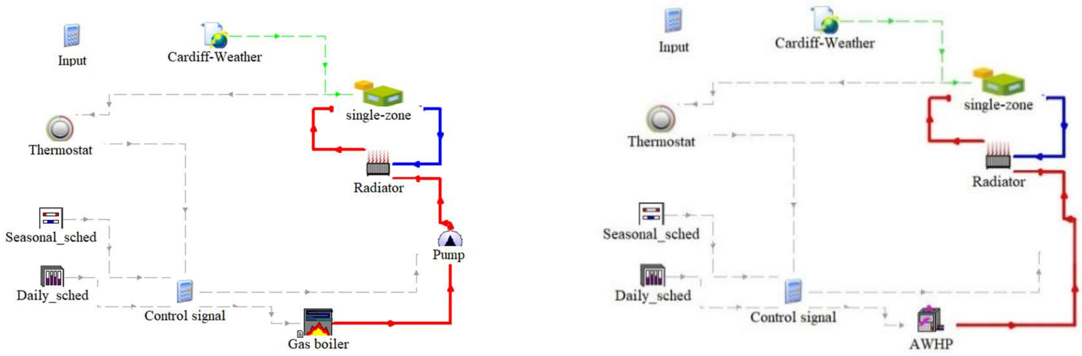
2.2. Modelling description

TRNSYS, a transient system simulation tool, was used to simulate the thermal behaviour of domestic building under two heating technologies: a gas boiler and an AWHP. Although for each heating technology, the model ran separately, the building characteristic remains identical. Key components of each technology are shown in Table 2.

Table 2. Components of the building energy model, including TRNSYS type, usage in the AWHP and gas boiler configurations, and a brief description of each component's function. Checkmarks (✓) indicate the presence of the component in the respective system.

Component	TRNSYS Type	AWHP	Gas boiler	Description
Gas Boiler	751.v2a		✓	HHV efficiency 86%; return temperature 50 °C, flow temperature 60 °C
AWHP	Type 525b.v2	✓		Operates in heating mode, return temperature 40 °C, flow temperature 50 °C; circulation pump integrated within the unit
Circulation Pump	114		✓	Single-speed; supplies radiator circuit
Radiator	1231.v2a	✓	✓	Water inlet from pump outlet; provides space heating
Thermostat	166	✓	✓	21 °C setpoint; controls boiler operation
Daily Scheduler	516	✓	✓	Defines daily heating profile
Seasonal Scheduler	515	✓	✓	Define seasonal heating profile

Fig. 3 illustrates the arrangement of the components in the gas-boiler and AWHP models in TRNSYS.



(a) Building model heated by AWHP

(b) Building model heated by gas boiler

Figure 3. Schematic of the building in TRNSYS.

The daily space-heating schedule used in TRNSYS model is according to the Home Energy Model (HEM) [18] and is given in Table 3.

Table 3 . Daily space-heating pattern according to the HEM.

Dat type	Heating pattern
Weekday	7:00–9:30, 16:30–22:00
weekends	8:30–22:30

In the TRNSYS model, the boiler or AWHP is enabled only when all below three controls are satisfied:

- The daily HEM schedule (Table 3)
- The seasonal heating pattern (between September and May)
- A room thermostat with a 21 °C setpoint.

In the market, radiator manufacturers typically specify radiators at a temperature difference (ΔT) of 50 K, as defined by BS EN 442 [19]. In the simulation, however, ΔT for the radiator was set to 34 K or 24 K, depending on the case study. ΔT is calculated as:

$$\Delta T = T_{mw} - T_{ind}$$

$$T_{mw} = \frac{T_{flow} + T_{return}}{2} \quad (4)$$

To align the simulation results with real-world products and estimate the closest available radiator capable of meeting the building's heat demand, the "required catalogue heat output" ($Q_{cat,l}$) was used, defined as:

$$Q_{cat,l} = \frac{Q_{total,l}}{f_1 f_2 f_3 f_4} \quad (5)$$

$Q_{total,l}$ denotes the total heat loss, f_1 is differential factor, f_2 is pipe connections factor, f_3 is enclosure factor, and f_4 is finish factor. These factors vary depending on the radiator's operating conditions and physical characteristics, and their corresponding values are provided in Table 4 [17]. Exposed pipework emissions were taken as zero.

Table 4. Factors (f_1 to f_4) used in calculating $Q_{cat,l}$.

Factor	Value
f_1	if ΔT = 34, f_1 = 0.606; if ΔT = 24, f_1 = 0.385
f_2	0.96
f_3	1
f_4	1

The heat capacities of AWHP ($Q_{cap,hp}$) and gas-boiler ($Q_{cap,bo}$) are selected for the maximum heat output of the radiators at the corresponding ΔT, as calculated using Eq. (5) and the parameters listed in Table 4. Accordingly, the capacities are defined as:

$$Q_{cap,hp} = Q_{cat,l} \ , \ Q_{cap,bo} = Q_{cat,l}$$

To estimate the domestic hot water (DHW) demand, it was assumed that the median daily DHW consumption for a typical UK household is 90 liters per day, increasing by approximately 16% during the colder months (September–May) compared with the summer period (June–August) [20] .Therefore, the required thermal energy for DHW (Q_{hw}) and electrical energy ($P_{hw,hp}$) is calculated as:

$$Q_{hw} = m \cdot c_p \left(T_{h,hw} - T_{c,hw}\right) \tag{6}$$

$$P_{hw,hp} = \frac{Q_{hw}}{COP} \tag{7}$$

Where $T_{c,hw}$ is the inlet cold-water temperature supplied to the AWHP for DHW, which is 10 °C, and $T_{h,hw}$ is the hot-water temperature, which is 45 °C. COP denotes the coefficient of performance of the heat pump simulated by TRNSYS.

For Space-heating demand, the values of COP and Q_{sp} were obtained directly from TRNSYS. Using these, the electrical energy of AWHP ($P_{sp,hp}$) for space heating is given by:

$$P_{sp,hp} = \frac{Q_{sp}}{COP} \tag{8}$$

According to Eq. (7) and (8), the total electrical consumption of the AWHP for space heating and DHW ($P_{total,hp}$) is given by:

$$P_{total,hp} = P_{hw,hp} + P_{sp,hp} \tag{9}$$

2.3. Case studies

Five case studies were defined as described below:

- Case 1- boiler with HEM schedule: The gas boiler supplies the building's heating demand and operates under the HEM schedule.
- Case 2- AWHP with HEM schedule: The AWHP supplies the building's heating demand and operates under the HEM schedule.
- Case 3- AWHP with preheat: The AWHP operates for four additional hours beyond the HEM schedule, two hours in the morning and two at night. The aim of this case is to evaluate the impact of extended preheating on indoor thermal conditions.
- Case 4- AWHP with 24-h heating: The AWHP does not follow the HEM schedule; instead, it operates to maintain an indoor temperature of 21°C throughout the day, evaluating the effect of continuous heating on indoor thermal conditions.
- Case 5- AWHP with upgraded radiators: The AWHP. The building's radiators are upgraded to a low-temperature model (ΔT = 24 K), and the AWHP size is adjusted accordingly to meet the revised heating demand and operates under the HEM schedule.

2.4. Validation

To validate the TRNSYS model analytically, the single-zone building was modeled as a uniform air volume, neglecting solar radiation, shading, ventilation, and infiltration effects. The thermal behavior of the building was represented using an R–C network approach, a common method in white and grey box modeling. This technique captures the dominant thermal dynamics through a physically meaningful arrangement of thermal resistances (R) and capacitances (C), while keeping the model computationally simple. Each wall of the building envelope was modeled using a 3R–2C configuration.

The complete R–C model of the single-zone building was implemented and simulated in Python over a 24-hour period. The air-to-water heat pump (AWHP) was defined with a heating capacity of 3 kW and operated between 7:00 a.m. and 12:00 p.m. (5 hours). The same operating conditions were applied to the TRNSYS model for comparison. The result of comparison between both models is illustrated in Fig. 4.

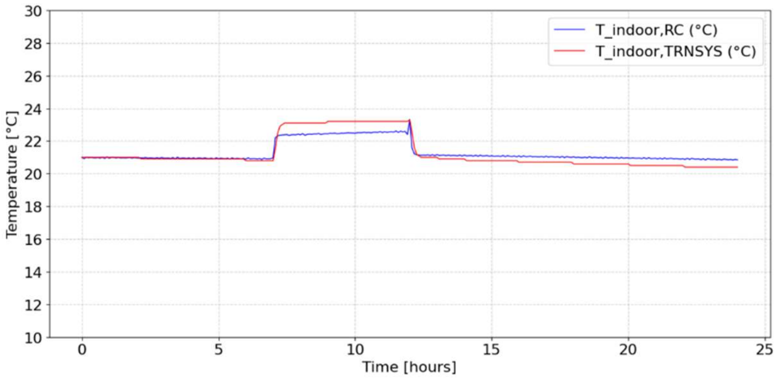


Figure 4. Results of comparison between R-C and TRNSYS models.

The agreement between the analytical R–C model and the TRNSYS simulation was evaluated using standard statistical metrics and summarized in Table 5. These results indicate that the R–C model with acceptable accuracy captures the dominant thermal behavior of the building, with only minor deviations from the TRNSYS simulation, likely due to modeling simplifications such as the lumped representation of the building thermal behavior.

Table 5. Validation metrics comparing the analytical R–C model and the TRNSYS simulation for indoor temperature.

Metric	Value
Mean Absolute Error (MAE)	0.33 °C
Root Mean Squared Error (RMSE)	0.41 °C
Coefficient of Determination (R^2)	0.83

2.5. Key performance indicators (KPIs)

2.5.1. Final energy demand

The annual final energy consumption for space heating is taken directly from the *TRNSYS* outputs, and DHW is calculated as explained in section (2.2). For AWHP, the required heat rate to raise the return water (T_{return}) to the user-defined flow (T_{flow}) setpoint is given by:

$$Q_{req,hp} = \dot{m}\, c_p\, (T_{flow} - T_{return}) \tag{10}$$

Where $\dot{m}$ mass flow rate of water and c_p is the water specific heat capacity. Then, the heat added to the liquid stream by the condenser is:

$$Q_{sp} = min\,(Q_{cap,hp}, Q_{req,hp}) \tag{11}$$

$Q_{cap,hp}$ is the AWHP's present capacity returned from the AWHP catalogue interpolation in *TRNSYS*. The total final electricity consumption for the AWHP to meet the building's heating demand is then obtained from Eq. (8) and Eq. (9). For the gas boiler, the required heat rate to raise the return water to the user-defined flow setpoint is:

$$Q_{req,bo} = \dot{m}\, c_p\, (T_{flow} - T_{return}) \tag{12}$$

and the heat added to the liquid stream by the boiler is:

$$Q_{sp,bo} = min\,(Q_{req,bo}, Q_{cap,bo}) \tag{13}$$

$Q_{cap,bo}$ is the boiler's present capacity returned from the gas-boiler catalogue interpolation in *TRNSYS*. from Eq. (6), the total heat provided by the boiler to meet the building's heating demand is:

$$Q_{total,bo} = Q_{sp,bo} + Q_{hw} \tag{14}$$

For boiler efficiency (η_{bo}), the required fuel input is:

$$Q_{fuel,bo} = \frac{Q_{total,bo}}{\eta_{bo}} \tag{14}$$

2.5.2. Running cost

This includes the sum of annual maintenance cost (Table 6), and the cost of final energy consumption, which is calculated based on two electricity pricing scenarios:

- Default tariff (DET): The default tariff, as defined by the Office of Gas and Electricity Markets (Ofgem), is the maximum price that energy suppliers can charge domestic customers for each unit of energy and the standing charge. This tariff is reviewed quarterly and provides a benchmark for regulated energy pricing.
- Dynamic tariff (DYT): Under a dynamic electricity tariff, prices change every half hour based on wholesale market conditions, reflecting real-time supply and demand. This tariff features lower prices during off-peak periods and higher prices during peak demand [21].

In all case studies using the dynamic tariff, the indoor temperature was controlled by the control strategy mentioned in section (2.2). In this work, all calculations for the gas boiler were performed using the default tariff.

Table 6. Annual running cost breakdown

Item	Value (£)
Annual final energy consumption cost	calculated in Figure 5
Annual gas-boiler maintenance cost	120
Annual AWHP maintenance cost	200

2.5.3. Percentage of time within comfort temperature (PCT)

This indicator represents the percentage of time in the heating season that the indoor air temperature remains within the thermal comfort range of 18 °C to 21 °C [22] under the model control strategy for each case. For example, in Case 1 (baseline), where the gas boiler operates under the HEM schedule, the PCT quantifies fraction of the heating season for which the indoor temperature is maintained within the comfort range according to the model output.

2.5.4. Upfront cost

This indicator refers to the initial investment required for purchasing and installing the heating system. In the UK, a £7,500 grant for air-source heat pumps is currently available [23] and is deducted from the total upfront cost. Initial investment cost breakdown is shown in Table 7.

Table 7. Initial investment cost breakdown

Item	Value (£)
AWHP purchase (3.5 kW) + installation (without radiator upgrade)	7,300
AWHP purchase (5 kW) + installation (with radiator upgrade)	11,500
New radiator purchase	250
Government grant (deduction)	7,500
Gas boiler purchase + installation	2,000

2.5.5. Annualized Net Present Value (ANPV)

The ANPV [24] converts future cash flows to present value for projects with different lifespans and is given by:

$$ANPV = \frac{r \times NPV}{1-(1+r)^{-n}} \tag{18}$$

n is the lifespan in year, r is the discount rate, and Net Present value (NPV) is defined as:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \tag{15}$$

With C_{in}, C_{out} denotes the income and expense in year t. Cash flow in year t (C_t) is defined as:

$$C_t = C_{in} - C_{out} \tag{16}$$

In this study, $C_{in} = 0$, since the focus is on the cost of using gas boiler and AWHP in domestic buildings individually. Hence:

$$C_t = -C_{out} \tag{17}$$

According to the Eq. (17), the value of ANPV will be negative. In economic decision-making, an alternative with a higher ANPV is considered more profitable over its lifespan [25].

3. Results and Discussion

Fig. 5 and Fig. 6 present the annual final energy consumption and annual energy cost for the domestic building model, respectively. As shown in those figures, upgrading the radiators to the low-temperature type, as part of a retrofit strategy, significantly reduces overall electricity consumption and annual energy cost compared with other cases. This improvement occurs because such radiators can deliver the required thermal output at lower supply temperatures, thereby enabling the heat pump to operate with a higher coefficient of performance (COP). In contrast, extending the heating pattern beyond HEM to preheat the building, as an alternative to radiator upgrades, increases both energy consumption and annual energy cost.

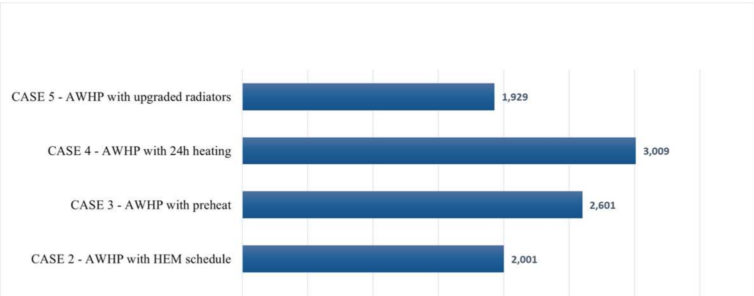


Figure 5. Comparison of annual final energy consumption for the domestic building model.

In Fig. 6, the default and dynamic tariffs apply only to electricity price, while natural gas price is calculated in this paper under default tariff. For this reason, it shows an equal annual energy cost for the gas boiler under both the default and dynamic tariffs. As it shows, using dynamic tariff for an AWHP across the four case studies in a domestic building can reduce the annual cost of energy compared with the default tariff.

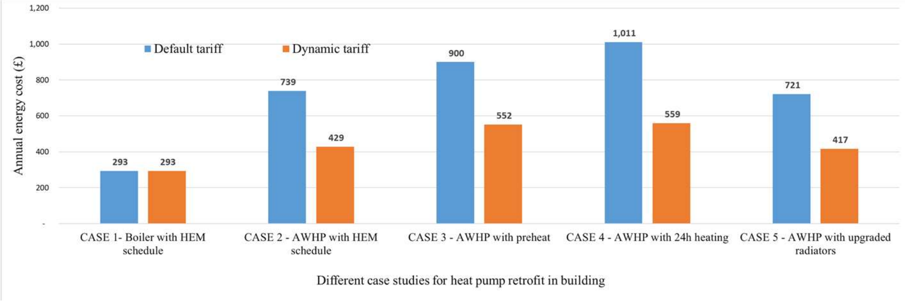


Figure 6. Comparison of annual energy cost for the domestic building model.

Fig. 7 presents the percentage of time within comfort temperature (PCT). As shown, operating the AWHP under the HEM heating pattern does not maintain the same level of thermal comfort as the gas boiler, since the AWHP cannot fully compensate for the building's heat loss during the HEM heating period. Extending the heating pattern can improve the PCT and increase it to a level even higher than that achieved by the gas boiler. For example, under the 24-hour heating pattern, the PCT reaches 99%, indicating that the indoor temperature remains within the comfort range for nearly the entire time. In comparison, upgrading the radiators alone provides a PCT similar to that of the gas boiler.

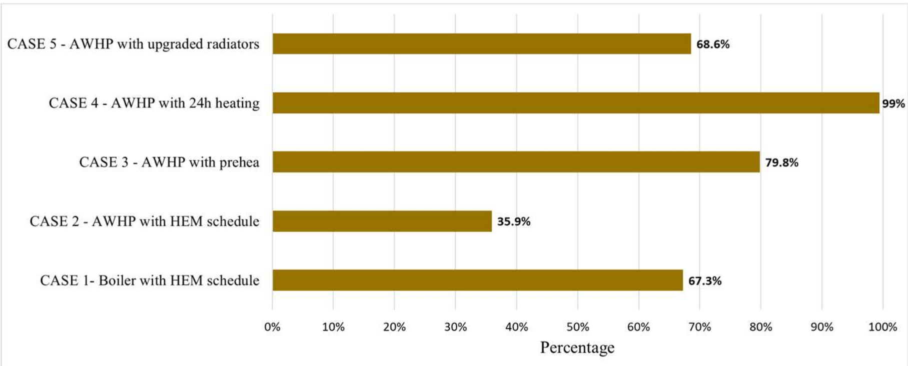


Figure 7. Percentage of time the building temperature remained between 18°C and 21°C.

Fig. 8 shows the comparison of ANPV for all cases. As shown, upgrading the radiators results in the highest ANPV, primarily due to the higher upfront costs associated with purchasing and installing new equipment. The result proposes that preheating building by extending the heating pattern beyond HEM will reduce the ANPV than the radiator upgrade.

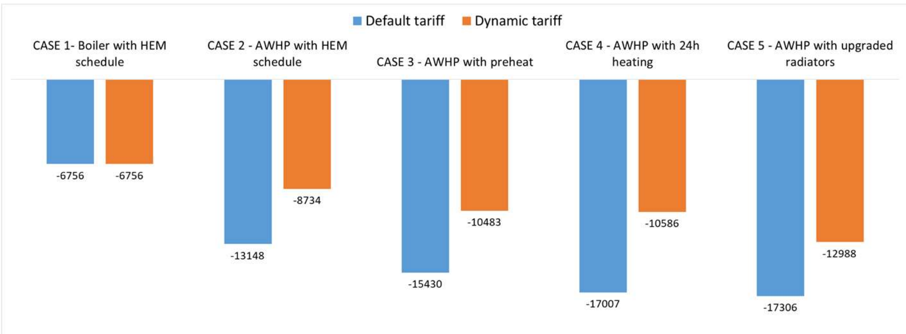


Figure 8. Comparison of ANPV for the domestic building model.

Fig. 9 presents the results of the techno-economic analysis, highlighting the trade-off between ANPV and PCT. For a consistent comparison in the spider plot, ANPV values were normalized across all cases. As shown, operating the AWHP according to the HEM heating pattern reduces costs, but the indoor thermal comfort provided by this approach is lower than that of a gas boiler, making it unsuitable for effective AWHP operation. The findings further indicate that, from an economic perspective, extending the heating pattern, in Cases 3 and

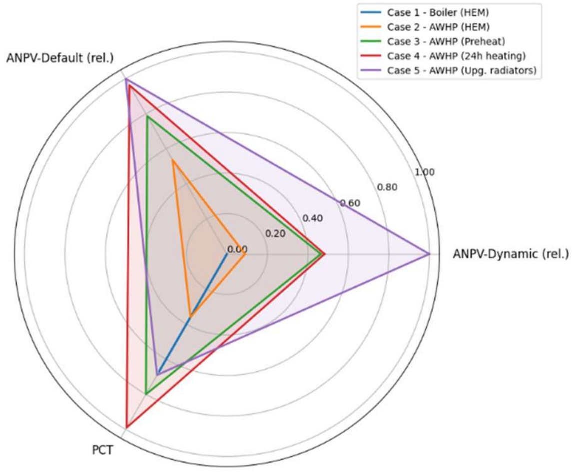


Figure 9. Comparison of ANPV and PCT for the domestic building model.

4 can achieve equal or even better indoor thermal comfort in domestic buildings at a lower cost than upgrading the radiators, as seen in Case 5, particularly under the dynamic tariff scenario.

4. Conclusions

The purpose of this study was to evaluate the retrofit strategies for adoption of air-to-water heat pumps (AWHPs) into typical UK dwellings by benchmarking several AWHP operating configurations against a gas boiler baseline. The results indicate that AWHPs can deliver equal or even greater levels of indoor thermal comfort compared to gas boilers when operated under an appropriate strategy, while economic performance is highly dependent on both the operating schedule and the electricity tariff.

In this work, two retrofit strategies for the adoption of AWHPs in domestic buildings were examined: (1) extending the duration of the heating schedule, and (2) modifying the existing heating system. The results show that extending the heating duration beyond the HEM schedule is more cost-effective than upgrading radiators, as it can achieve comparable or even higher indoor thermal comfort than a gas boiler at a lower cost.

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