Energy Performance Assessment of Gas Boilers, Air Source Heat Pumps and Insulation Type Pairings in UK Dwellings

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Abstract

Domestic heating through conventional means is responsible for 62% of carbon emissions in the UK's built environment, which certainly will slow down and hinder the UK's target of Net-Zero Carbon by 2050. Air Source Heat Pump (ASHP) is a promising way to heat homes with low carbon emissions. However, poorly insulated houses can limit the efficiency of ASHPs, and thus weaken the system performance especially during cold days. This paper assessed multiple design options of a typical UK dwelling with varying strategies of heating systems (gas boilers and ASHPs) and building fabric insulation pairings for reducing heating system carbon emissions and improving overall energy efficiency. Through IES VE energy modelling, it was found that the highest energy saving about 53% and 44% reduction of carbon emission can be achieved in the peak winter month (January) by means of well insulated building fabric in association with ASHP over gas boiler with the equivalent building insulation. The clear benefit of the adequately insulated dwelling was also apparent with a yearly mean 58% reduction in fabric heat loss against inadequate insulation. This paper contributes to the matters concerning the integrated effect of building insulation and low-impact heating systems on dwellings' energy performance during heating season.

Key Innovations

- A variety of different pairings of conventional and low-impact domestic heating systems and building fabric insulation types were simulated
- Energy saving and carbon emission reduction potential through conventional and low-impact domestic heating systems with different building fabric insulations were estimated

Practical Implications

In this study, different energy models were developed to simulate the uptake of air source heat pumps and fabric insulation for dwellings in the UK context. This, in turn, will serve as a role model for the synergetic research and development of low-impact domestic energy systems and housing retrofits within the Global South context in response to environmental deterioration.

Introduction

In the UK's built environment, about 48% of carbon emissions come from the existing housing stock, and 62% of this is from heating (UKGBC, 2021). To meet the UK Government's commitments to Net-Zero Carbon by 2050, the way homes are heated must be changed from current conventional methods (such as gas boilers) to more sustainable methods such as heat pumps. The use of heat pumps in dwellings can look to significantly reduce a household's carbon emission from heating as well as help reduce running costs (Zhang et al., 2017).

In terms of heat pump technologies, air source heat pump (ASHP) is proven to be an ideal option for dwellings than other heat pump types due to its accessibility, lower life cycle cost and higher efficiency (Kegel et al., 2012; Christodoulides et al., 2019), which has been promoted by the UK Government's "Boiler Upgrade Scheme" (BEIS, 2022). However, ASHP's efficiency tends to decrease during the periods of severe cold, and therefore weakens its heating performance (Hakkaki-Fard et al., 2015). Consequently, the building fabric certainly will need to compensate for the loss of thermal heat. As a matter of fact, according to the Housing Survey of the UK (DCLG, 2017), 20% of housing stock in the UK is more than 150 years old, and 40% was built before 1944, which comes with less insulation leading to heat dissipation through building fabric quickly.

The current rate at which heat pumps are installed or retro-fitted is far from what is expected with less than 100,000 installations annually in the past two years (as shown in Figure 1), and it is estimated that over 1 million yearly fittings will be required to meet the Net-Zero target (HPA, 2019). Furthermore, research report that heat pumps are not widely adopted in UK homes due to the major limiting factor of poor energy performance of the majority of the housing stock (Lingard, 2021).

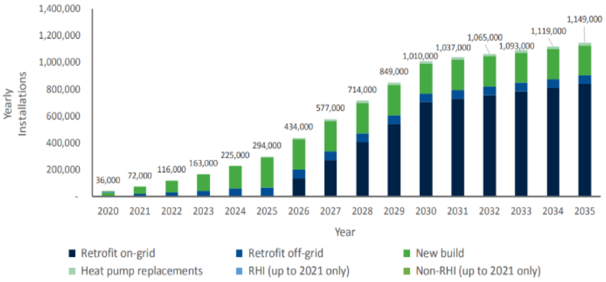

Figure 1: Yearly heat pump installations (HPA, 2019).

Therefore, it is crucial to retrofit the UK dwellings while changing the domestic heating systems to prevent energy wastage. However, old dwellings with conventional solid walls of less thermal insulation present challenges to modern houses with adequately insulated cavity walls (Dowson et al., 2012). Thus, the gap between the adaptability of ASHP and uninsulated homes should become the focus of research within the built environment, which has sought to explore the possibilities of a balanced solution.

Research recently pointed out that there is a lack of concern on synergising heat pump performance and building fabric insulation in relation to the UK dwellings (Lingard, 2021). Therefore, questions still stand on if a sustainable heat source is sufficient alone to reduce a household carbon footprint without an adequate insulation of building fabric. This study aims to investigate the benefits and/or the drawbacks of different insulation types of typical UK dwellings when paired with conventional gas boilers or ASHPs for reducing domestic heating energy demand and carbon emission and improving energy efficiency and overall feasibility.

Methods

In this paper, there were three separate heating systems and building fabric insulation pairings were used to provide different systems characteristics and admittance properties for a two-bed bungalow in London (case study building), being:

- Gas boiler with adequate insulation
- ASHP with adequate insulation
- ASHP with inadequate insulation

The spaces and building dimensions are outlined in Table 1, while the floor layout is illustrated in Figure 2. It should be noted that all spaces in the bungalow were 2.5 metres in height. IES VE simulation was used for the proposed study in terms of building energy modelling. Given that IES VE energy simulation has been well validated over the years, so it can be confidently used to analyse complex scenarios with bespoke design solutions, especially for the proposed desk research which was subject to inaccessibly experimental conditions for the specific heating systems and housing retrofits.

Table 1: Spaces and building dimensions.

Space	Width (m)	Length (m)	Area (m^2)	Volume (m^3)
Entrance	1.5	1.5	2.25	5.625
Hallway	11	1.5	16.5	41.25
Bathroom	4	3	12	30
Bedroom 1	3	4.5	13.5	33.75
Bedroom 2	4	3	12	30
Kitchen / Living / Dining	6.5	4.5	29.25	73.125
Building	9.5	9	85.5	213.75

Figure 2: Floor layout of the case study building.

Building fabric and thermal properties

In this study, thermal insulation of the building fabric was considered a predominant factor in reducing energy consumption and carbon emission alongside the use of ASHP, which was reflected through both adequate and inadequate insulations. The inadequate insulation can be referred to external air cavity wall plus double glazing with an air gap, which has been widely used since the 1970s and is an assumption of minimum insulation in homes across the country (UWE, 2009). Where the insulation is adequate, this can be referred to external wall with cavity insulation plus double glazing with argon gas filled gap (EST, 2022a; EST, 2022b). The two separate construction design options' U-values used within the IES VE models are represented in Table 2, these materials created building fabric templates based on typical situations.

Table 2: Construction materials and thermal properties.

Material/Element	U-value ($W/m^2 \cdot K$)
Internal ceilings/floors[1]	1.08
Internal partitions[1]	1.78
Doors[1]	2.19
Roof[1]	0.18
External wall cavity insulation[2]	0.17
Double glazing argon gap[2]	1.60
External wall air cavity[3]	1.04
Double glazing air cavity[3]	1.93

[1] *Used in all three IES VE design options*

[2] *Used in IES VE design options with adequate insulation*

[3] *Used in IES VE design option with inadequate insulation*

The simulation models used the desired design criteria to influence heat loss calculations using the general element conduction formula and the facades heat transmission coefficient formula as follows:

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho c}{\lambda} \cdot \frac{\partial T}{\partial t} \tag{1}$$

$$H = \sum A \times U + \sum l \times \Psi + \sum x \times n \tag{2}$$

Where T is the temperature difference over the façade element, ρ is the solid density, c is the specific heat capacity, λ is the solid thermal conductivity, t is the time for heat transfer, A is the area of façade element, U is the thermal transmittance of façade element, l is the length of thermal element, Ψ is the heat loss along a metre of junction between two thermal elements, x is the point thermal bridge, n is the number of point thermal bridges.

Building operation criteria

To gauge a realistic and fair test, the three IES VE models used the constant variables as follows:

- Building footprint
- Method of thermal energy transfer
- Location
- External temperatures
- Internal temperature set points
- Internal heat gains
- Ventilation method
- Operational profile (weekly use profiles)

The building was a typical two-bed bungalow with common spaces that would use radiators. The location was London Heathrow, and all models used the same weather file having identical weather patterns throughout the yearly cycle. The heating design setpoint of internal temperatures was 21°C based on the recommended comfort criteria defined in CIBSE Guide A (CIBSE, 2019). Internal heat gains account for an occupancy density of 3 persons with sensible and latent gains was of 70 W and 45 W, respectively, per person. Additional miscellaneous internal gains such as artificial lighting was accounted for on a W/m^2 basis, which was assumed as 10 W/m^2. Natural ventilation was specified with an air changes per hour (ACH) rate of 1. Operational profiles were set to a typical weekly profile consisting of operating hours for weekdays and weekends/holidays. Weekdays operating hours were 06:30-08:30 and 17:00-23:00, while weekends/holidays were operational between 08:00-23:00.

Heating systems' characteristics

The ASHP option for this research introduced a commercially available product – Mitsubishi Electric Ecodan R744 QUHZ-W40VA Monobloc Air Source Heat Pump (Mitsubishi Electric, 2022). The gas boiler option used a Baxi 224 Combi 2 boiler with an efficiency of 87.6% (Baxi, 2022). In the IES VE model, the ASHP's coefficient of performance (CoP) was used to gauge the ratio of heat output to power supplied using the formula below:

$$CoP = \frac{Q}{W} \tag{3}$$

In this study the ASHP with a CoP of 1.98 would produce 4.32 kW of heat for every 2.18 kW of power supplied. The CoP of the ASHP decreases with the decrease of the ambient air temperatures, and therefore the ASHP would become less efficient in colder days.

Data application and analysis

The IES VE models used the ASHREA climate design conditions in modelling the bungalow's geometry where design criteria were applied. The construction and thermal property templates were applied to differentiate between insulation options of external walls and double glazing types where U-values were applied based upon Table 2. Heating templates were created to differentiate between ASHP and gas boiler systems performance criteria. A whole year operating cycle simulation was used, which allowing for an accurate analysis of the varying three different design options would take place.

It should be noted that gas boiler with inadequate insulation was not considered one of the design options, as it is clearly unsustainable, while gas boilers are likely to be banned from new UK homes by 2025 (The Guardian, 2020).

Results

All results of the proposed study were based on a full year cycle for accurate representation. The results collated were as the following three aspects:

- Total system energy consumptions
- Total system carbon emissions
- External wall transmitted heat losses

Results of the three aspects were collected from three separate models of heating and insulation options and arranged into a single chart that represent the data making for easy comparisons. The details of the results are further specified in the following paragraphs.

Total system energy consumptions

As shown in Figure 3, both ASHP scenarios showing the significant reduction in system energy consumption in winter months (November – January) in comparison with the gas boiler scenario. With adequate insulation, the biggest disparity was found in January, in which the ASHP was about 53% more efficient than that of the gas boiler. A similar yet not as significant increase of 26% efficiency was shown with the ASHP with inadequate wall insulation in the same month, which, however, demonstrated the benefit of ASHP in minimising energy consumption and is considered more sustainable.

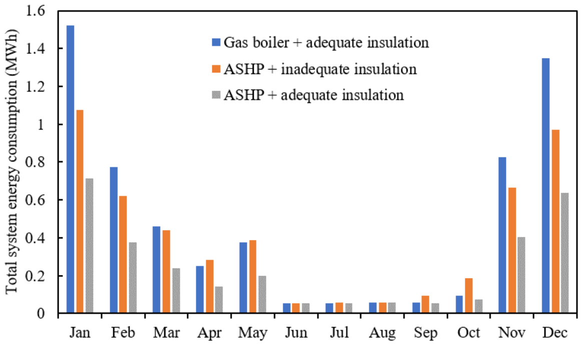

Figure 3: Comparison of total system energy consumptions.

During summer months energy consumption significantly dropped, as the climate was generally warmer and reduced the need of the system to run during this time. Thus, the results showed minimal benefits between systems and building fabrics during the summer months. Following this situation, when perceiving the mean average value, the summer months are discounted.

The yearly mean peak operating time energy consumption reaffirm the efficiency benefits of an ASHP system to gas boiler. Specifically, the simulation results also showed the gas boiler mean energy consumption was 633 kWh, while the inadequately insulated wall with ASHP provided an efficiency increase of 17% to a mean consumption of 525 kWh and a further 66% increase of efficiency when the external walls were adequately insulated to a mean consumption of 215 kWh.

Total system carbon emissions

The results of system carbon emissions show similar trends as the system energy consumptions. As can be seen in Figure 4, the adequately insulated building with ASHP system had the lowest carbon emissions over the winter months. The highest reduction of carbon emission using ASHP in comparison with gas boiler was around 44% (equivalent to 291 kgCO$_2$), which was found in January, while the inadequately insulated ASHP scenario still had a reduction of 13%.

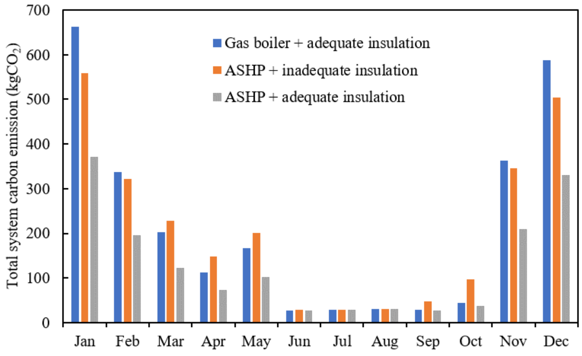

Figure 4: Comparison of total system carbon emissions.

Similar to the system energy consumptions, the reduction in carbon emissions significantly dropped across all scenarios in summer months. This was again due to the warmer climate and operating hours for heating were significantly reduced as the set point was commonly achieved naturally within the building resulting in less running time. With this accounted for the simulation demonstrates a yearly mean 41% reduction in carbon emissions using ASHP in adequately insulated dwelling to the gas boiler scenario and a negligible 2% reduction for the inadequately insulated walls with ASHP.

Furthermore, the ASHP with inadequately insulated wall scenario under-performed and created more emissions than the gas boiler scenario during the shoulder months. This again shows the importance of the thermal insulation for homes.

External wall transmitted heat losses

In terms of thermal insulation, Figure 5 shows a clear benefit between external air cavity wall plus double glazing with air gap (that is, inadequate insulation scenario) and external wall with cavity insulation plus double glazing with argon gas filled gap (that is, adequate insulation scenario). The results show that when adequate insulation was provided alongside the heating systems, there was an annual mean 58% reduction in heat loss with reference to the inadequate insulation scenario. This pattern was found throughout all months of the year.

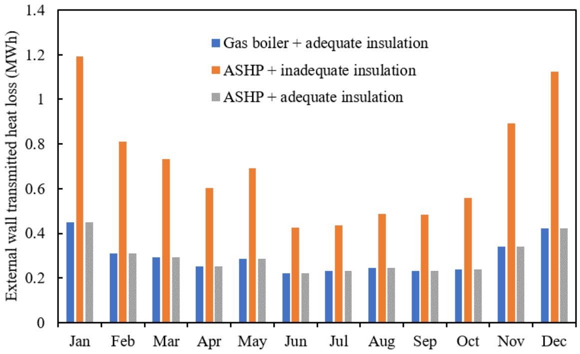

Figure 5: Comparison of external wall transmitted heat losses.

Discussion

The findings for the three pairings of heating systems with different building fabrics respond to whether insulating UK homes is the first option rather than initially looking to completely change a heating system. The IES VE simulation results show that the uptake of a more sustainable heating system, such as ASHP, might not always make less overall impact on the environment. In some months of the year, a gas boiler system equalled or even bettered the energy performance and carbon emission levels than that of an ASHP system with inadequate insulation for the building.

Having a lack of adequate insulation was proved to be worse for the environment. During warmer months, it was found that energy consumptions and carbon emissions levelled off and were negligibly different, which, however, should not cast doubt on the effectiveness of the ASHP system with adequate insulation due to the energy savings and sustainability benefits across the remainder of the year. The energy savings would help work towards the reductions required to meet the UK Government's commitments to Net-Zero Carbon by 2050.

The results presented in this study also reveals that a dwelling with adequate insulation was rather crucial on top of the improvement of heating system efficiency.

Conclusion

Based on IES VE simulation for the multiple design options of a typical UK dwelling with varying strategies of gas boilers and ASHPs and building fabric insulation pairings, the optimal design option was found from a sustainability and feasibility outlook. Basically, the results show that adequate insulation was imperative to accessing an ASHP's maximum potential in heating the dwelling; otherwise, the system (ASHP) might not be significantly better than conventional gas boiler systems. Specifically, the optimal design option could reduce energy consumption up to 53% and 40% of carbon emissions than the conventional methods during heating period.

This study somehow identified, in the UK context, conceptually preliminary solutions in addressing the gap between the adaptability of low carbon heating systems and uninsulated dwellings, which will dedicate to achieving low-impact domestic heating and therefore ensuring residents' well-being in a sustainable way. Furthermore, this study and its subsequent research can serve as a role model for the synergetic research and development of low-impact domestic energy systems and housing retrofits within the Global South context in response to environmental deterioration globally.

Nomenclature

Symbols

A	area of façade element [m^2]
c	specific heat capacity [J/kg·K]
l	length of thermal element [m]
n	number of point thermal bridges [-]
T	temperature difference over façade element [°C]
t	time for heat transfer [h]
U	thermal transmittance of façade element [W/m^2·K]
U-value	thermal transmittance [W/m^2·K]
x	point thermal bridge [W/K]

Greek symbols

λ	solid thermal conductivity [W/m·K]
ρ	solid density [kg/m^3]
Ψ	heat loss along a metre of junction between two thermal elements [W/m·K]

Abbreviations

ACH	air changes per hour
ASHP	air source heat pump
CoP	coefficient of performance

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