The Impact of Baseline Wall U-Value on Energy Performance of Solid Wall Insulation

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Abstract

Solid wall dwellings are in high energy demand and need to be treated by energy retrofit measures such as internal wall insulation (IWI). U-value is the key parameter for energy saving evaluations. There are uncertainties about the U-values of solid wall properties in literature which has led to under/over estimation of IWI performance. So, this paper investigates the energy performance of IWI pre and post insulation for Salford Energy House (SEH), the replica of a pre-1919 Victorian solid wall terraced house. IES-VE was used to develop a model for SEH and the model was validated against the collected experimental data. The base line solid wall U-values were changed between 0.64-2.48 W/m²K to assess the benefits of insulation for different solid walls. The results showed that annual heating energy saving varies significantly depending on the base line wall U-values ranging from 19% to 46.2%. The cost saving potentials as a result of energy saving varied by £228 per year between the cases with lowest and highest base line wall U-values. Furthermore, thermal comfort (18°C<T<=23°C) was improved and annual reduction of 1248 kg CO_2e was achieved. Overheating was not significant for the case study using Manchester weather data since a small increase in %hours in which the temperature was above 23°C was observed after insulation. The result of this paper contributes towards better understanding of energy saving potentials of IWI within the UK and provides a more realistic picture of the IWI benefits for policymakers and relevant stakeholders.

Introduction

The UK government has recently established an ambitious emission reduction target to achieve net zero emissions by 2050 Waite (2020). To achieve this goal, residential buildings will play an important role as this sector is the second largest energy consumer in the UK with emission level of over 69.1 $MtCO_2$e in 2018 Waite (2020). There are about 25 million homes in the UK in which around 30% are solid wall houses, and about 36% of carbon emission from domestic sector belongs to those solid wall dwellings Hansford (2015), Loucari et al. (2016). So, solid wall insulation (SWI) could be a potential solution to meet the Greenhouse gas (GHG) reduction target of the UK by 2050 Elderkin (2011). However, SWI installation has not been widely spread across the UK and the potential of energy saving and CO_2 reduction of the wall insulation has not yet been achieved Elderkin (2011), CCC (2015). Despite all the policies, subsidies and grants available for SWI such as the Government's Energy Company Obligations (ECO) scheme, only 9% of houses with solid walls are insulated by the end of 2019 and around 7.7 million houses are still remained uninsulated Oxley (2020). Lack of clear information about potential benefits of SWI was amongst the main SWI barriers that discourages householders from retrofitting their premises Wilson et al. (2014), Weeks et al. (2015). Therefore, the benefit of SWI such as energy saving, cost and emission reduction should be evaluated more clearly to improve the householders awareness about the SWI advantages, leading to informed dicision-making and unlocking the demand.

Comparing external and internal insulation, preserving the external aesthetical feature of the solid wall houses was one of the barriers slowing down the application of wall insulation in solid wall houses Moorhouse and Littlewood (2012), Moran (2014), Haines and Mitchell (2014). In these cases, internal insulation would be more preferable as external aesthetical feature of the properties remain unchanged Brannigan and Booth (2013), BRE (2014). Furthermore, the retrofit process can be faster for internal works as in most cases planning permission are required for external insulation. Also, internal wall insulation (IWI) is cheaper CJ Morris (2014) and can lead to more heating energy savings compared to external wall insulations Loucari et al. (2016), Brannigan and Booth (2013), Loucari et al. (2016).

Despite some government reports and reviews, the number of scientific publications for SWI is limited in the literature. In some related publications, the retrofit was studied for case studies which were not solid wall dwellings originally. The limited existing studies on solid walls tended to investigate the combination of different retrofit measures as a package, one of which would be the wall insulation. So, the body of the works that have been published to date can not clearly reveal the actual potential of energy savings and CO_2 emission reduction from wall insulation. One of the first publications about retrofit in solid wall houses was a research conducted in 1983 Freund (1983). Two unoccupied 50-year-old semi-detached solid wall houses were selected as the case studies for the retrofit by using a number of energy efficacy measures in each case study.

According to the literature, U-value is the key parameter for developing energy saving estimation and there are uncertainties about the U-values of solid wall properties which could lead to the under/over estimation of SWI performance BRE (2016), Loucari et al. (2016). This discrepancy can easily lead to miscalculation of the carbon reduction potential and mislead the zero-emission target. The common U-value assumption for solid wall houses were about 2.1 W/m^{2}K in previous studies, however, there were some concerns about the overestimation. Recent works has proved that U-values of solid wall houses should be lower than 2.1 W/m^{2}K which was generally assumed BRE (2016), Loucari et al. (2016). This overestimation can cause a significant unrealistic estimation in CO_2 saving potential up to 65% Loucari et al. (2016). In this concept, Building Research Establishment Ltd. (BRE) suggested a revised U-value for solid walls BRE (2016). They conducted field works, experimental research as well as the theoretical work about thermal performance of solid walls. Their results revealed that 2.1 W/m^{2}K for U-value of the uninsulated solid wall needs to be revised to 1.75 W/ m^2 K. However, this revised U-Value still contradit with some studies in the literiture. For example, in a study about importance of U-value by Li et al. (2015), the uncertainty of the energy performance estimation was observed due to the variation in U-values assumptions for solid walls. The results of this study for 40 brick solid walls and 18 stone dwellings revealed that the wall mean U-values were in the range of 1.3 ± 0.4 W/m^{2}K, which was significantly different from 2.1 W/m^{2}K given initially in guidelines CIBSE (2006), BRE (2012) as well as the revised value of 1.75 W/m^{2}K suggested by BRE. This variation in U-values was the main driving force for developing this study to quantify the potential energy savings and CO_2 reduction of SWI for a range of U-values obtained from literature.

This study aims to present the potential saving of IWI as a single retrofit measure in solid wall houses for different solid wall U-values and Air Permeabilities (AP) measured previously in the literature. To achieve this goal, Salford Energy House (SEH) was modelled as a solid wall case study in IES-VE. Experimental data including building properties, room temperature and energy performance for SEH was obtained and the IES-VE model was validated against those experimental data to achieve a precise model of the case study. This model was then used to explore the potential benefits of IWI in terms of the energy saving, thermal comfort and CO2 reduction for a variety of baseline U-values ranging from 0.64 W/m^{2}K to 2.48 W/m^{2}K when insulated by a commercially available IWI material with high thermal resistance and two improved AP values (AP_1 and AP_2) after insulation. The indoor temperature changes after the internal wall insulation were investigated. The cost analysis was also performed to highlight the monetary values of the energy savings.

Methodology

The SEH is a full-scale replica of a solid wall house located within a climate-controlled chamber in University of Salford and it is similar to a pre-1919's Victorian end terrace houses. The SEH was constructed by using reclaimed materials and traditional methods of the time, such as lime mortar, lath and plaster ceilings. Such properties are in considerable need to improve their energy efficiency due to their high AP and lack of insulation. Since the building has located in a controlled environment, collected data can offer extremely precise information to validate the model and analyse the actual performance of the solid wall houses. The experimental data including heating energy consumption (gas) and room temperatures were collected for analysing the performance of SEH as a solid wall case study house. The measured data such as AP and U-values alongside with building specifications were used in developing and validating the IES-VE model to extend the analysis to the interest of this research. Figure 1 shows the schematic diagram for the methodology of this work which will be discussed in more details in following two sections.

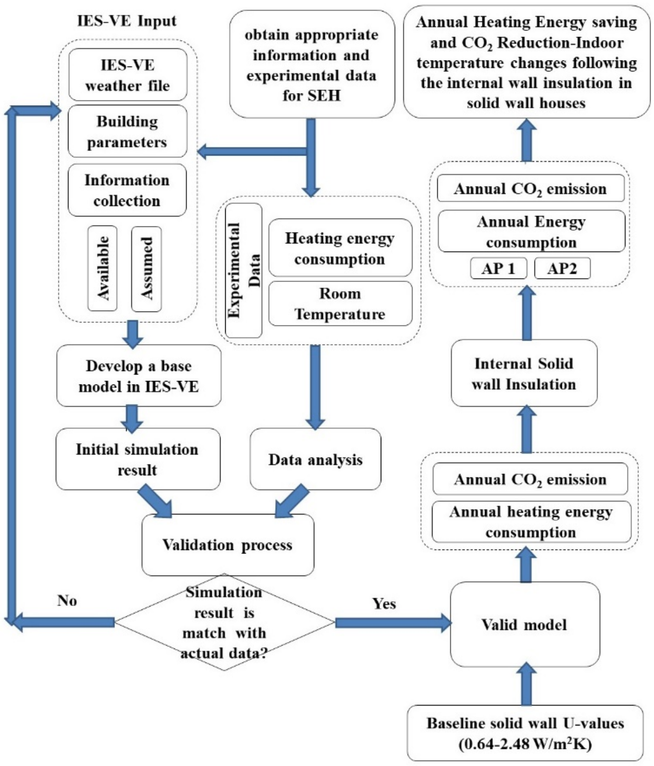

Figure 1.Schematic diagram of the research methodology.

A) Experiments

The experiments were conducted in steady-state condition where the chamber temperature was aimed to be maintained at 5°C constantly representing a cold day of winter and the gas consumption and room temperatures were measured every minute for a period of 7 days. The experimental data was then converted to daily consumption for gas and hourly for temperature to be comparable with IES-VE output results. The heating system of SEH is a condensing combi boiler with heating unit capacity of 32 kW and efficiency of 93%. In this study, no occupant schedule was considered during the experiment to identify the building performance with no interference to obtain more accurate results. Taking out the occupant factor in SEH facility for the purpose of this study, will help to avoid the gap between the model and real building performance data since occupant behaviour was seen to be one of the main source of the disagreement between the predicted and real building performance Housez et al. (2014) Gupta and Gregg (2015). The building specifications such as U-values and AP values were measured in previous research studies for SEH and those values were used in developing the valid model of SEH alongside the precise floorplan from the accurate building measurements. The building construction details of SEH which was used in the IES-VE model are presented in Table 1.

Table 1. Construction details of SEH.

Parts	Construction details	U-Values (W/m^2K)
External walls	225mm brickwork + internal plastering	1.56
Partition walls	Internal – 13mm plastering + 115mm brickwork + 13mm plastering	1.88
	Party wall – Plastering + 225mm brickwork	1.56
Ceiling	Suspended timber frame + lath & plaster	0.46
Roof	Stone chipping + Felt/Bitumen Layers + Slate Tiles	5.03
Floor	Synthetic Carpet + timber flooring + Plaster (lightweight) Gypsum Plastering	1.97
Glazing	6mm Pilkington single glazing	3.6

B) Simulation and validation

Figure 2 presents the floor plan and 3D view of the developed model of SEH in IES-VE. The measured input data of the SEH such as U-values and the average measured AP of 13.95 m^3/m^2h, measured in previous study using this facility by Marshall et al. (2017), were imported into the IES-VE model to develop the valid model. The heating profile was also modelled to reflect the settings of the thermostatic heating controllers inside the house during the experiment. Using the in-situ measured data such as U-values and APs for developing the model, provided us with a more reliable simulation analysis compared to other related modelling studies. This approach was also emphasised in literature to minimise the performance gap between the model and reality Marshall et al. (2017), Ji et al. (2019).

The simulation results for hourly room temperatures and daily gas consumption for heating were compared with experimental data to validate the SEH model, ensuring a highly reliable computational model is developed for this study. Figure 3 presents the sample of validation process for Bedroom 1 and Lounge for one day of the experiment. As can be seen, the trends are quite similar confirming a good agreement between the experimental data and IES-VE simulation results. Also, the temperature set-points for Lounge was higher compared to Bedroom 1 which is similar to other living spaces.

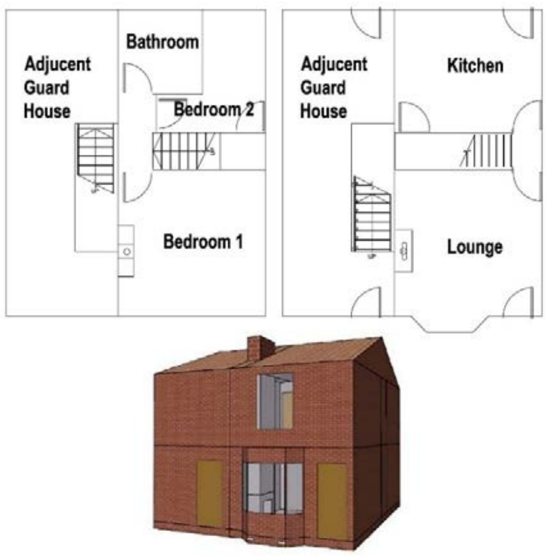

Figure 2. The SEH IES-VE model.

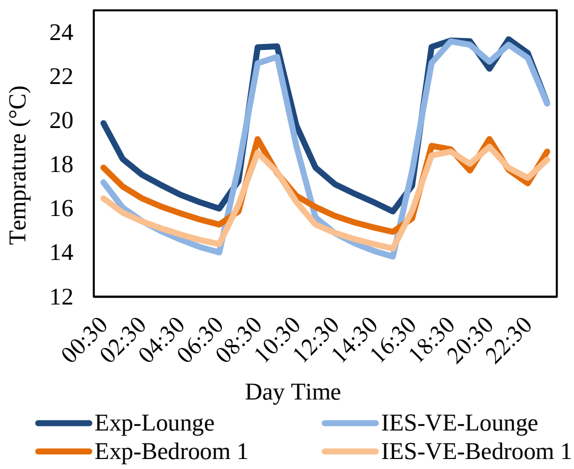

Figure 3. Temperature profile form experiment and IES-VE simulation.

The valid model was used to simulate annual heating energy and house temperature for the SEH in the real situation by using the weather file for an example weather year in Manchester (ManchesterEWY). To develop our sensitivity analysis, the U-value was changed between 0.64 W/m²K to 2.48 W/m²K for base line solid walls without insulation as reported by the Society for the Protection Ancient Buildings (SPAB) for the solid brick walls Rye and Scott (2012). Such variations in wall U-values provide a better picture of possible energy saving and CO_2 emission improvement by SWI for solid wall houses with different brick fabric characteristics.

Furthermore, the model was insulated by an IWI material of high-quality polyisocyanurate which was offered by a reputable company as the best insulation material claiming to be "an excellent thermal resistance and cost-effective option". Insulation laminate board should be fixed to the 25 mm batten fixed on the internal wall surface to prevent the risk of cold bridging Pullen (2020). This instruction was followed in IES-VE software to model the wall insulation. The specifications of the insulation material are given in Table 2.

Table 2. Insulation Laminate board specifications Knaufdrywall (2012).

P'board Thickness (mm)	Insulation board Thickness (mm)	Thermal Conductivity (W/mK)	R-Value (m²K/W)
9.5	65.5	0.022	3

Following the wall insulation, ventilation heat loss through the fabric reduces with higher effect for the IWI compared to the external resulting to reduce the AP Moran (2014). The AP determined in the building regulation as suggested by the SAP is less than 10 m³/m²h 50pa. The AP improvement of up to 57% was reported in a study by Energy Saving Trust as a result of IWI in solid wall properties Stevens et al. (2013). Hence, two values for APs were selected for developing the analysis in this paper; in which one is the standard level of AP_1=10 m³/m²h and the other is more optimistic value of AP_2=6 m³/m²h assuming 57% improvement compared to pre-insulation value of 13.95 m³/m²h can be achieved. The models with prementioned range of U-values for both AP_1 and AP_2 were simulated and the results including the heating energy were extracted and cost savings and CO_2 emission reduction for insulated solid brick walls were calculated. Also, the internal temperature changes for the range of below 18, thermal comfort range (18 °C to 23 °C) and above 23°C for baseline models and insulated models were assessed to identify the effect of IWI on inside temperature and the possible overheating.

Discussion and result analysis

The model of SEH was accurately validated against experimental data and high accuracy was achieved with the minimum performance gap compared to the experimental data (percentage error is below 1% for daily heating energy consumption (gas) and Root Mean Square Error (RMSE) of 0.7 °C-1.5 °C for temperatures of the different rooms.

Figure 4 shows the annual energy consumption of the SEH valid model pre and post IWI. To simulate the insulated walls, the U-value of the walls were changed from 1.56 W/m²K to 0.2593 W/m²K and the results were

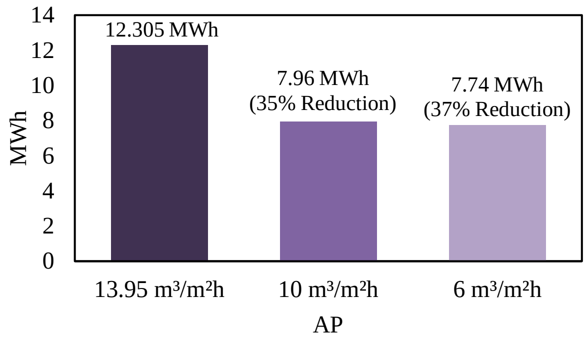

Figure 4. Annual heating energy use pre and post IWI in SEH case study (base line wall U-value of 1.56 W/m²K).

Table 3. Annual heating energy saving and CO_2 reduction potential of IWI in solid wall house with base line wall U-value of 1.56 W/m²K.

SEH validated model		
In situ U-value (W/m²K)	**1.56**	
AP (m³/m²h)	13.95	
Annual Heating Energy Consumption (MWh)	12.305	
Insulated walls		
U-value insulated wall (U_{IW}) (W/m²K)	**0.2593**	
AP (m³/m²h)	**Ap_1**	**Ap_2**
Annual Heating Energy Consumption (MWh)	7.96	7.74
Annual Energy Saving (MWh)	4.35	4.57
Annual Energy Saving (%)	35.35	37.14
Annual CO_2 reduction (kg CO_2e)	800	840.2
Annual cost saving £	198.4	208.4

Table 4. Heating energy saving and CO_2 reduction potential of wall insulation in solid brick walls houses with base line wall U-value in range of 0.64 W/m²K to 2.48 W/m²K.

Base line walls												
In situ U-value (W/m²K)	**0.64**		**1.05**		**1.4**		**1.75**		**2.1**		**2.48**	
AP (m^3/m^2h)	**13.95**											
Annual Heating Energy Consumption (MWh)	9.403		10.77		11.83		12.82		13.74		14.71	
Internally Insulated walls												
U-value insulated wall (U_{IW}) (W/m²K)	**0.2096**		**0.24**		**0.2544**		**0.2641**		**0.2709**		**0.2763**	
AP (m^3/m^2h)	**Ap_1**	**Ap_2**	**Ap_1**	**Ap_2**	**Ap_1**	**Ap_2**	**Ap_1**	**Ap_2**	**Ap_1**	**Ap_2**	**Ap_1**	**Ap_2**
Annual Heating Energy Consumption (MWh)	7.62	7.4	7.81	7.6	7.92	7.7	8.01	7.8	8.07	7.9	8.14	7.92
Annual Energy Saving (MWh)	1.8	2.01	3	3.19	3.91	4.13	4.82	5.04	5.7	5.9	6.6	6.8
Annual Energy Saving (%)	19	21.35	27.5	29.62	33.05	34.9	37.6	39.3	41.3	43	44.7	46.2
Annual CO_2 reduction (kg CO_2e)	328	369	544	586	719	759	885	927	1042	1083	1208	1248
Annual cost saving £	82.1	91.7	136.8	145.5	178.3	188.33	219.8	229.8	259.9	269.0	301	310.1

extracted for AP_1=10 m^3/m^2h and AP_2=6 m^3/m^2h. As shown in Figure 4. the heating energy use of 12.31 MWh was reduced to 7.96 MWh and 7.74 MWh after insulation with AP_1=10 m^3/m^2h and AP_2=6 m^3/m^2h, respectively. It means the annual energy savings of between about 35% to 37% can be achieved by IWI depending on AP values.

Typically, gross calorific value (CV) for each kWh of energy savings is used for reporting the CO_2 emission as used in this study. Furthermore, the value of 0.18385 kg CO_2e per kWh, obtained from UK Government GHG Conversion Factors 2019 was employed for CO_2 emission calculations in this paper BEIS and DEFRA (2019). The savings of 800 kg CO_2e (with AP_1) and 840.2 kg CO_2e (with AP_2) can be achieved following the wall insulation for the model with base line wall U-value of 1.56 W/m²K as presented in Table 3. The average gas unit rate of 3.8 pence/kWh (ex VAT) was extracted from a retailer website UKPower (2020). VAT was added in cost saving calculations of IWI and the value of 4.56 pence/kWh was used in all cost analysis. The results showd that the cost saving of between £198 to £208 per year, can be achieved. This saving is considerable comparing to the average gas bill price of £676 for household in the UK in 2018 Rowe (2019).

To extend the analysis of IWI for solid houses similar to the SEH type (end of terraced houses), the model was simulated for variety of base line wall U-values and the simulation results was presented in Table 4. According to the results, for the solid wall houses with different base line U-values ranging from 0.64 W/m²K to 2.48 W/m²K, the annual heating consumption changed between 9.4 MWh to 14.7 MWh. It means the annual energy saving was between 19% to 46.2% depending on the U-values and APs. As expected, the higher energy saving was achieved for solid wall houses with higher base line wall U-values compared to those with lower baseline wall U-values. Also, the insulated model with AP_2 showed about 0.2 MWh/year reduction in heating energy use, compared to the same insulated model with AP_1 for different cases. To assess the corresponding environment impacts of wall insulation, the annual CO_2 reductions (kg CO_2e) were calculated and presented in Table 4 as well. The high CO_2 reduction with large discrepancy from 328 kg CO_2e to 1248 kg CO_2e were observed for different solid wall houses which highlights the importance of the baseline U-values in estimating the potential CO_2 reduction of SWI. So, the policy makers should reflect on this finding when planning for the CO_2 emission reduction target of the solid wall houses. Furthermore, the potential cost saving of IWI was calculated and presented in Table 4. As shown, the cost saving changed between £82.1 to £310.1 annualy depending on U-values and APs. It also shows a significant variation in potential cost saving which can mislead the homeowners in decision making towards the implementation of IWI as well as the policy makers in offering the right incentives.

Temperature inside the insulated houses are expected to be higher compared to homes with no insulations. To reveal the precise impact, the total %hours per year that the house spaces were in the temperature range of below 18 °C, between 18°C and 23°C and above 23°C, pre and post insulation were extracted from the model and presented in Figure 5 for SEH validated model with baseline U-value of 1.56. After wall insulation, the reduction of more than 3% in total hours when the temperature was below 18 °C and increase of more than 2% and 1% for the range of 18 °C to 23 °C and above 23 °C, respectively (see Figure 5).

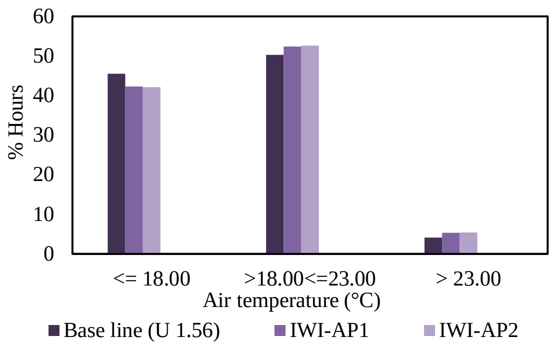

Figure 5. Annual effect of insulation on indoor temperature for SEH (base line U-Value=1.56 W/m²K).

The results for other base line wall U-values are presented in Table 5. As shown, the annual %hours in which the temperatures were below 18°C was 43.3% for base line wall U-values of 0.64 W/m²K. This was reduced to 42% in insulated case for AP_1 and to 41.7% for AP_2 representing 1.3% and 1.6% reduction, respectively. Moreover, by increasing the base line wall U-values from 0.64 W/m²K to 2.48 W/m²K, a continuous reduction in %hours per year that the house temperatures were below 18 °C was observed after insulation for both AP_1 and AP_2 with the maximum reduction of 4.9% (from 47.1% to 42.2%) for AP_2. On the other hand, the annual %hours in which the temperature was between 18 °C and 23 °C were increased by 0.2-3.7 % for AP_1 and 0.4-3.8 % for AP_2 depending on the base line U-values. There was also an increase of 0.9-1.2 % for AP_1 and 1.1-1.3% for AP_2 for the temperature above 23°C. These results suggested that the house is getting generally warmer as more temperatures are in or above thermal the comfort range.

The possibility of overheating (temperature above 23°C) pre and post wall insulation was investigated in more details for the lowest and highest baseline U-values of solid walls during a year and the results are presented in Figure 6. The results of the model with baseline wall U-value of 0.64 W/m²K showed that for 3.8% of the hours, the temperature was between 23°C to 28°C. Following the wall insulation, this was increased to 4.8% and 4.9% for AP_1 and AP_2, respectively. In this case, the annual % hours of the temperature above 28°C, was increased only around 0.1% for both AP_1 and AP_2 while it mainly happened in the loft spaces.

Similarly, the model results for 2.48 W/m²K base line wall U-value showed for 4.3% of the hours the temperature was between 23-28°C in a year. After the wall insulation, the annual %hours increased by 0.8% and 1% reaching to 5.1% and 5.3% for AP_1 and $AP_{2,}$ respectively. For the temperature range of above 28°C, the increase of around 0.1% for both AP_1 and AP_2 was identified as well, while the majority of this increase occurred in the loft spaces with negligible effect in other spaces.

Table 5. Annual effect of insulation on indoor temperature.

Base line wall U-values (W/m²K)	**Base line models**			**Internally Insulated models**					
	AP=13.95 m³/m²h			**AP_1=10 m³/m²h**			**AP_2=6 m³/m²h**		
	%Hours T<= 18 °C	**%Hours 18°C <T<=23°C**	**%Hours T> 23°C**	**%Hours T<= 18°C**	**%Hours 18°C <T<=23°C**	**%Hours T> 23°C**	**%Hours T<= 18°C**	**%Hours 18°C <T<=23°C**	**%Hours T> 23°C**
0.64	43.3	52.8	3.9	42	53	5	41.7	53.2	5.2
1.05	44.4	51.5	4.1	42.2	52.6	5.2	41.9	52.8	5.3
1.4	45.3	50.6	4.2	42.3	52.4	5.3	42	52.6	5.4
1.75	46	49.7	4.2	42.4	52.3	5.3	42.1	52.5	5.4
2.1	46.6	49	4.4	42.5	52.2	5.4	42.2	52.3	5.5
2.48	47.1	48.4	4.5	42.5	52.1	5.4	42.2	52.2	5.6

The bedroom 1 was the only space which experienced temperature above 28°C only for 2 hours pre wall insulation (about 0.001 %hours annually), however, temperature over 28°C was observed in bathroom and lounge as well as the bedroom 1 during the year after the wall insulation for 3, 5 and 11 hours for AP_1 and 4, 5 and 15 hours for AP_2, respectively. Also, it should be noted that about 95% of the all recorded temperatures above 28°C for pre and post wall insulation occurred in warmer season between May-July. Some simple measures such as night ventilation and shading were suggested in the literature to overcome the overheating effects Gupta and Gregg (2013), Tink et al. (2018). This issue can be further investigated in future studies by considering the effects of the global warming.

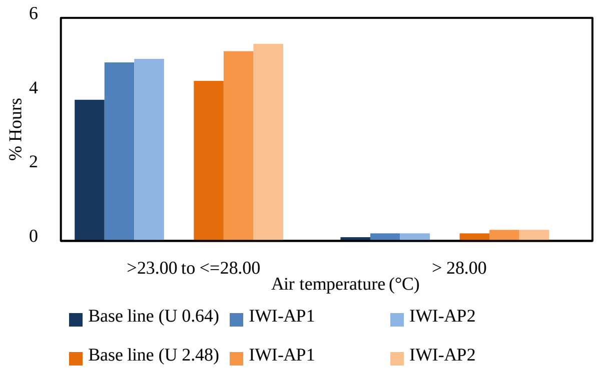

Figure 6. Annual effect of insulation on indoor overheating temperature.

Conclusion

The benefits of internal wall insulation for a variety of solid wall U-values were investigated in this paper with an accurate validated model. While the results and analysis were developed based on the simulation, in-situ measurement of software input data such as U-values and APs as well as the precise validation process was performed to develop a reliable model with minimum performance gap with actual experiment.

As demonstrated, uncertainties in U-value of solid walls may result in significant over/under estimation of potential savings of solid wall insulation. The results suggest that the IWI can save more energy in the solid wall houses with higher U-values as their base line energy use is significantly high. As the baseline wall U-value decreases from 2.48 to 0.64 W/m²K, the energy saving potential reduces from 46.2% to 19% which is still a significant figure for energy saving and the corresponding cost saving varies between £310.1 to £82.1, respectively. The analysis of the energy saving revealed that IWI is an effective measure for retrofitting the solid wall houses and should be prioritised in retrofitting the solid wall properties. The large discrepancy was observed in energy saving and CO_2 emission reduction in solid wall houses depending on the base line U-values. This finding is very important for setting the emission target reduction for solid wall homes by regulatory bodies, policymakers and relevant stakeholders.

The internal temperature variation within and out of thermal comfort range was also evaluated in this paper. In general, temperature increases in insulated houses with higher effect in houses with higher baseline wall U-values. Thermal comfort was improved in all cases, however, the % hours in which temperature was above 23°C increased by wall insulation. In this study, overheating was not significant considering the small increase in %hours in which the temperature was above 23°C after wall insulation. Overheating effect inside the houses was observed in warmer seasons even before insulating the walls and the increase of temperature over 28°C on living spaces was negligible post wall insulation. The effects of possible heating penalties in warmer seasons due to the global warming effects should be considered for evaluating the more realistic saving potentials of IWI in future research about solid wall properties. The result of this paper presented a more convincing figures for energy saving, CO_2 reduction and cost savings potential of IWI in solid wall houses to facilitate the understanding of the IWI saving benefits for more informative communications with householders who are going to decide about any retrofit measure in their solid wall properties.

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