# Comparative thermal response of internally and externally insulated houses

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**Abstract:**
When retrofitting older properties with solid outer walls additional insulation if required has to be added to the inner or outer surfaces of the outer wall. The choice and viability of either of these solutions is largely determined by cost, appearance, room dimensions and the physical practicalities and details of fitting the insulation, particularly at openings. Less attention is often paid to the change in thermal response of the buildings that result from internal and external insulation. This paper describes and compares the modelled dynamical thermal responses of a retrofitted traditional solid-walled house when externally or internally clad with insulation. A set of parametric studies was carried out using dynamic thermal simulations coupled with a nodal network airflow model, to evaluate the thermal responses of a Victorian type end-terrace house using current Test Reference Year (TRY) weather data as well as the 'morphed' future weather data. The simulation results demonstrate the likely performance of the house with various retrofit measures, having implications for occupant comfort, for seasonal heating and cooling strategies, and for overheating evaluation during summer if ventilated passively. The responses in cold winter and hot summer conditions are significantly different showing characteristics typical of heavyweight and lightweight constructions.
**Keywords**:
Thermal dynamics, modelling, retrofit, insulation, housing.

## 1 Introduction

In most older UK houses the external envelope was designed using available local materials, often stone or brick, to exclude or to resist the weather, mostly the wind and rain and direct solar radiation. Little consideration was given to the thermal conduction characteristics of the external envelope. In the earlier part of the 20$^{th}$ century external wall cavities, usually around 50 mm wide, were introduced to reduce the chance of water penetration from the outside through to the inside. Later, to improve comfort and to reduce heating demand, the wall cavities of these existing houses began to be filled with insulation, usually by blowing in granular, closed cellular or fibrous material that provided thermal insulation but not a conducting path to enable water to penetrate. More recently, in new build, in response to rising fuel costs, environmental concerns and to comply with changes in building regulations, cavities have been made wider, typically 100-200 mm wide, and filled with rigid or granular insulation. This is an elegant, hidden, solution. It incurs an additional cost in the extra space taken up by the increased wall thickness and the extra insulation required, and care has to be taken to ensure structural integrity. However, when the cavity width is optimised – typically at 150-250 mm in the UK climate (Randell & Hoyle, 1979 and Webster, 1987), these initial extra costs are quickly recovered in improved comfort and reduced heating costs.

In retrofitting older properties with solid outer walls additional insulation if required has to be added to the inner or outer surfaces of the outer wall which are then clad appropriately, usually on the inside with plasterboard or on the outside with a proprietary finish designed for weather protection and attractive visual appearance that must also comply with local regulations particularly in Conservation areas. The choice and viability of either of these solutions is largely determined by cost, appearance, room dimensions and the physical practicalities and details of fitting the insulation, particularly at openings. However, little consideration is often given to the effect on the dynamical thermal response of a house when it is internally or externally insulated. This paper considers how the thermal response is affected by internal or external insulation and the implications for occupant comfort, for seasonal heating and cooling strategies, and for overheating in summer if ventilated passively.

If a house is insulated internally the substantial external wall mass is on the outside of the insulation, exposed to the external climate but insulated from the interior. Consequently the effective 'thermal storage capacity' of the house is reduced, in some cases very substantially. In such a house the internal temperature should respond more rapidly to thermal inputs or external temperature variations. This can be advantageous as a cold house can be quickly heated but has disadvantages as internal temperature variations will be greater, requiring faster response control systems to maintain stable temperatures and the increased risk of overheating. If a house is externally insulated the substantial wall mass is on the inside of the insulation, protected from the external climate but exposed to the interior. The effective 'thermal storage capacity' will be increased and the house should take on more of the characteristics of a well insulated heavyweight house.

## 2 The Salford Energy House Model

The Salford Energy House (EH hereafter) is a replica of a pre-1920's Victorian type, end-terrace house, located within an environmentally controlled laboratory at Salford University. The EH was reconstructed using the traditional methods of the time including lime mortar, lath and plaster ceilings. Within the current UK housing stock, about a fifth are of this type. They tend to be leaky, lack insulation, and their energy efficiency is low compared with new built housing. The purpose of the EH is to provide a facility where new technology and solutions may be tested to improve its energy efficiency, so that these proven technologies and solutions can then be made available to the building industry. The EH design is used in this study to model the effects of adding insulation internally or externally.

The EH model is a 3D numerical model constructed in IES [IES VE 2011]. IES VE is a well established thermal simulation tool for analyzing the dynamic responses of a building based on the hourly input of weather data. Figures 1a and 1b show the plan view of the house, a typical two-bedroom house with a dining kitchen and a living room. The condition void is there to provide an adjacent environment to simulate a neighbouring dwelling to the end-terrace house. An axonometric view of the EH model is shown in Figure 1c. The EH is built on top of a concrete base and vents are provided for the raised timber ground floor. The fireplace is not in use due to the restriction of the testing environment within the laboratory, the chimneys shown here are for illustration only.

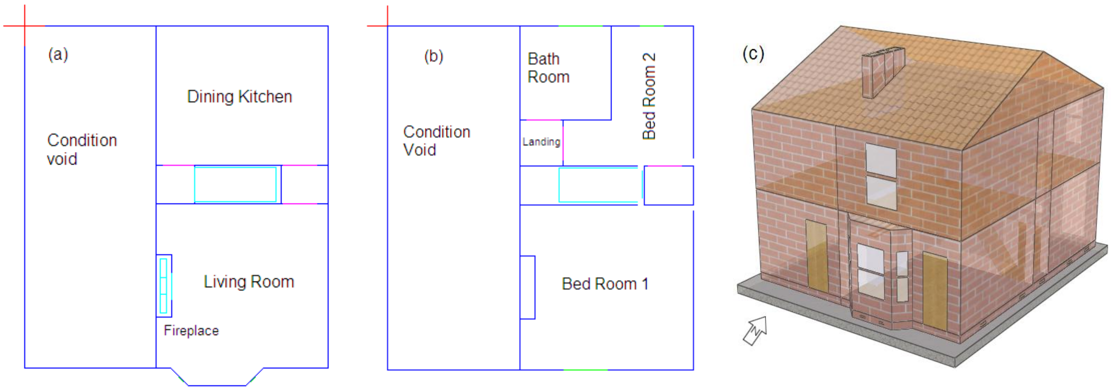


Figure 1. The EH model, (a) ground floor plan, (b) first floor plan, and (c) 3D view

The construction materials used for the EH are reclaimed materials from local sources in order to make this testing dwelling as close as the pre-1920's Victorian terrace houses. The details of the construction are shown in Table 1.

Table 1. Construction details of the EH (used in the modelling).

| Parts | Construction details | U-Values (W/m$^2$K) |
|---|---|---|
| External walls | Terrace house – 225mm brickwork + internal plastering;<br>Condition void – 200mm lightweight concrete block + 45mm Polyurethane board* | 2.05<br><br>0.32 |
| Partition walls | Internal – 13mm plastering + 115mm brickwork + 13mm plastering;<br>Connection to Condition void – Plastering + 225mm brickwork | 1.97<br><br>1.59 |
| Ceiling | Suspended timber frame + lath & plaster | 1.46 |
| Roof | Stone chipping + Felt/Bitumen Layers + Cast Concrete + Slate Tiles | 3.35 |
| Floor | Synthetic Carpet + timber flooring + Plaster (lightweight) – Gypsum Plastering | 1.18 |
| Glazing | 6mm Pilkington single glazing | 5.56 |

*In the modelling, a thin plastering layer was added to the Polyurethane board to avoid numerical instability.

Within the database of the modelling tool, the exact representation of how the building was constructed may not be possible, for example, window and door frames. The effects of that level of details is considered by mathematical representation (airflow through cracks) rather than 'drawing' them on the model physically. The rule of thumb is to represent the thermal properties as closely as possible. The materials given in the table are close representations of what are used in the building.

## 3 Modelling considerations

The purpose of this modelling process is to use the Energy House as a Base Model (BM), by varying parameters such as heating set points, insulation levels, weather files as well as the background infiltration rates, to evaluate the energy demands for keeping the house at the required thermal condition. The indicative results provided by this process will offer a better understanding of to what extent the EH can be improved in terms of energy efficiency, and the likely thermal performances of the building.

### 3.1 Life patterns

The house is assumed to be occupied by two working adults. Their daily living patterns are assumed and shown in Figure 2. In reality people are not going to experience their lives as repetitively as this, the way their lives are arranged is to make the modelling process more explicit and manageable. The patterns define when and where the occupants are in the house. This is relevant to the incidental gains from occupants as well as from the lighting and household equipment gains when they are present.

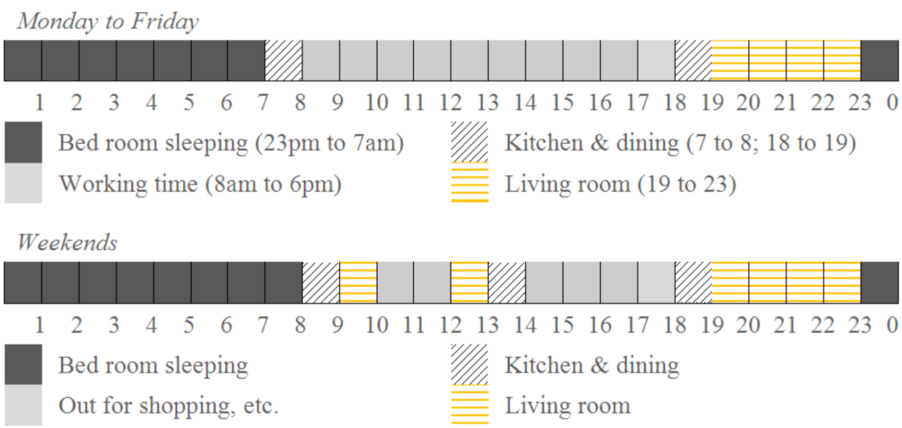

Figure 2. Living patterns of the occupants

### 3.2 Heating set points and incidental gains

Relevant to the life patterns above, from Monday to Friday, heating is set from 6am to 8am and 6pm to 11pm. The heating set point is 20°C for the base model; for weekends, heating is set from 7am to 10am; 12 noon to 2pm and 6pm to 11pm. Lighting gain is assumed to be 7.2W/m2 when needed. There are other incidental gains in the kitchen and living room when occupied. The air infiltration level is assumed to be at 0.7 air changes per hour (ach). This is an average value used for UK domestic housing from the work of Stephen (1998). To avoid excess heat building up in the summer time during occupancy, the sash windows of the living room are allowed to open. Similar routines are used for kitchen and bedroom windows.

The EH base model is first simulated, and by varying the heating set points only (from 18°C to 24°C), the modelling outputs are expected to provide a correlation between the heating set points and the annual energy demands.

### 3.3 Adding insulation

The EH is considered to be hard to treat in terms of adding insulation due to its solid wall construction. The insulation could either be added internally or externally in theory, while in reality, which approach will be used depends on the house owner's preference, subject to the restrictions of local councils if external cladding is considered. In the modelling both internal and external insulation were tested individually to Building Regulation Part L1B (2010) level (for exposed external walls, second floor ceiling, but not for the floor at the ground level). Further improvements were made to replace all the external glazing from Pilkington single glazing to standard low-e double glazing. With added insulation and the replacement of single glazing to double glazing, the air tightness of the building is expected to be improved. A background infiltration rate of 0.5 ach is then assumed, an amount considered to be sufficient to provide enough fresh air for occupants and prevent mould growth in buildings (Ridley et al 2006). A range of thicknesses of insulation was tested both internally and externally. For internal insulation, thicknesses are from 50mm to 100mm; externally, the range was extended to 200mm. This is believed to cover most of the insulation levels used for retrofitting domestic housing in the UK building industry.

### 3.4 Varying infiltration rates

Part of the space heating energy is used to heat up the cold infiltrating outside air to the desired temperature. The rest is for heating up the building fabrics as well as the heat losses through them. Although it is considered to be problematic when background infiltration rate is lower than 0.5 ach in terms of occupant health and mould growth, a wider range of infiltration rates is tested by the model to examine the amount of energy used due to ventilation when the EH base model is externally insulated to the 2010 level regulations, with double glazing. The test infiltrate rates are 0.7, 0.5, 0.3, 0.1 and 0 ach.

### 3.5 The EH thermal performances

Retrofitting dwellings tend to focus on their energy efficiency. With increased insulation and air tightness, there are potential impacts on the ventilation effectiveness and thermal comfort after improvements are made. In particular, with potentially elevated temperature in the future, these dwellings may be facing challenges of overheating in summer. These aspects were considered by modelling the EH using both current and 'morphed' future projected weather files (Belcher et al 2005). When the EH is insulated internally, it can be regarded as a lightweight construction. If insulation is put externally, the construction can be regarded as heavyweight due to the large thermal mass exposed to the internal environment.

## 4 Results and Discussion

The annual energy demands for space heating at various set points are shown in Figure 3. It is almost linear for the temperature range tested, with more heating energy needed for higher temperatures. As a rough estimate for every 1°C increase of the heating set point the energy demands needed to keep the house at that temperature will be increased by 10%. The way a house is heated also plays an important role in space heating energy consumption. The circle on Figure 3 represents the annual heating demands for the base model at 20°C set point, but with the house constantly heated to the set point. This results in a more than 60% increase in demand at the same set point.

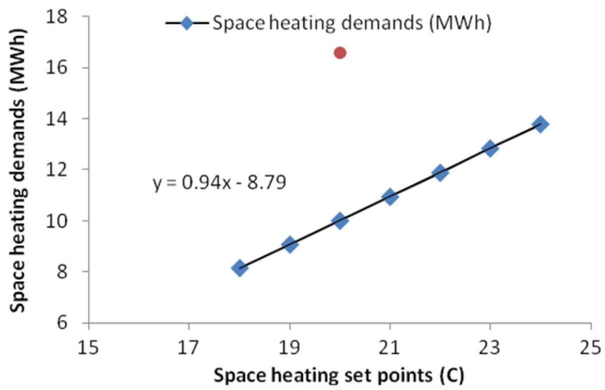

Figure 3. Space heating demands at various heating set points.

When testing internal insulation, 58.5mm Dense EPS Slab Insulation (Like Styrofoam) was added with a layer of plastering for the internal finishing; externally, the same level of insulation and external brickwork. For the second floor ceiling, 134.5mm GLASS-FIBRE QUILT is added. The resulting U-values for the walls and roof are 0.35 and 0.25 $W/m^2K$. The ground floor of the EH is a raised timber framed floor, above a concrete base. No extra insulation is provided so that the U-value is constant at 1.18 $W/m^2K$ for all the modelling cases presented in this work. Figure 4 shows that more than 40% of the original space heating demands are saved due to the added insulations to the exposed external walls and first floor ceiling; roughly another 10% energy saving for space heating can be realized by replacing single external glazing by standard low-e double glazing. Adding the influence from the potentially increased air tightness, the total reduction in energy demands for space heating is about 60%. With space heating taking up nearly two-thirds of the total domestic energy usage and 27% of the total carbon emissions of the UK coming from domestic homes, reducing space heating energy consumption has importance in meeting the nation's ambitious target to cut carbon emissions by 80% by 2050 (Killip 2008) as well as practical benefits for individual home owners.

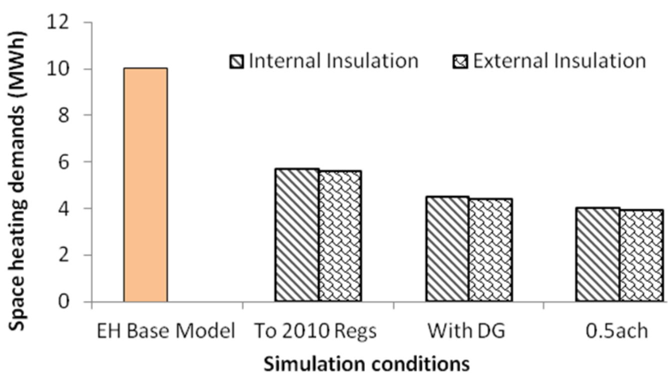

Figure 4. Comparisons between the EH base model, with insulation internally and externally, low-e double glazing and increased air tightness.

It is worth noting that, due to the thermal responses of heavyweight/lightweight construction there is a slight difference in annual space heating demand made by insulating walls internally and externally. Although the overall saving in space heating energy is minor for heavyweight construction the differences of dynamic thermal performances between heavyweight and lightweight construction can be substantial.

Figure 5 shows annual space heating demands for varying insulation thicknesses both internally and externally. The thickness ranges given here are those commonly used in the building industry for domestic housing improvement. There are obvious improvements from adding insulation, however, the rates of gain decrease with added thickness. For example, with 50mm insulation, the achieved energy saving on space heating is about 60% compared with the EH base model (ref. Figure 3 at 20°C); increasing insulation up to 200mm, the extra reduction is less than 10%. This may indicate that heat losses through roof, ground floor and ventilation are playing a more significant role than the exposed walls when their insulation has reached a certain level. The optimization of insulation thickness for exposed walls depends not only on the level of insulation of other parts of the building and the amount of ventilation, but also on the costs of the insulation materials and of putting them in place. Therefore, in practice, there is a limit to ‘the more, the better’.

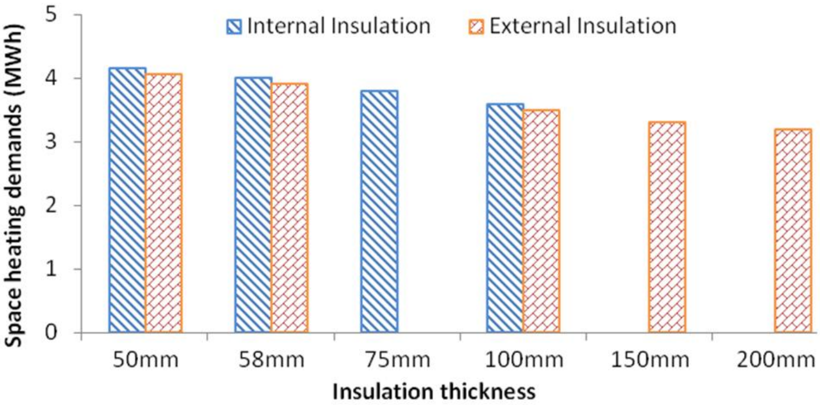

Figure 5. Annual space heating demands with levels of insulation on exposed walls.

Varying infiltration rates of the EH base model with external insulation to Part L1B (2010) affect heating demands needed for warming the ventilation air to desired temperature (Figure 6, 20°C is the set point for this case).

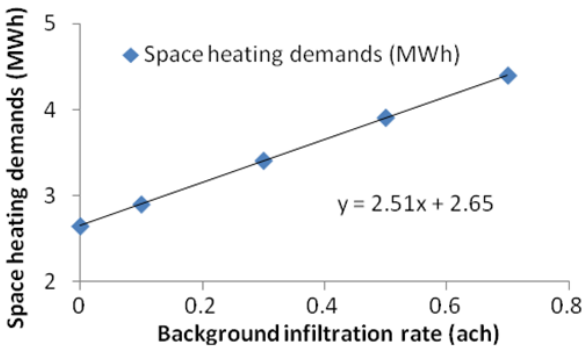

Figure 6. Space heating demands vs background infiltration rate

When infiltration rate is 0.7 ach, 40% of the total space heating energy is used to warm the outside air. Increasing air tightness can increase the energy efficiency. However, infiltration rates lower than 0.5 ach during occupancy may be considered to be inadequate for fresh air. For new built dwellings the background infiltration can be well below this value so manually controlled venting facilities such as trickle vents, are often provided for occupants' comfort.

It is evident that energy efficiency is among the top concerns when refurbishing existing housing stock. On the other hand, occupancy comfort level, especially overheating during hot summers, should also be evaluated in line with any 'improvements' made to the dwellings. With potentially elevated climate temperatures in the future there is an increasing need to address this aspect. If external climate temperatures rise as anticipated, the annual heating demands could decrease due to the projected weather conditions in the future as shown in Figure 7.

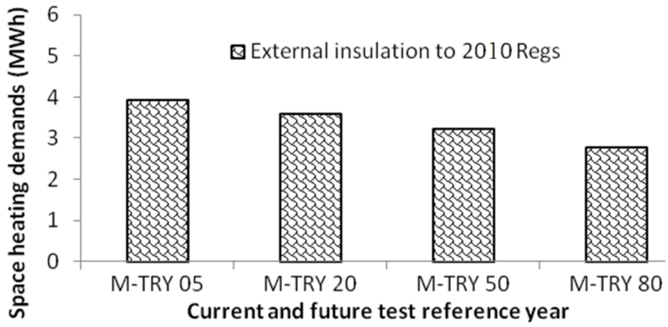


Figure 7. The EH base model with external insulation to 2010 Regs, modelling results using Manchester Test Reference Year (TRY) 2005, and future projected weather year of 2020, 2050 & 2080.

Exposed thermal mass is much larger when adding insulation externally than when it is added internally for the EH base model. As discussed earlier, when energy efficiency is concerned, the differences between the two are minor with the external insulation option performing slightly better. Figure 8 shows the Dry Resultant Temperature (DRT) in the living room during cold winter and hot summer weather. DRT variations with internal insulation are greater in both cases. This shows that heavyweight construction (external insulation option) tends to be better in stabilising internal environment, with a lesser degree of oscillation compared with lightweight construction. The resulting difference may be just 2°C, which does not seem to be a great deal, however, the accumulated effects can be important.

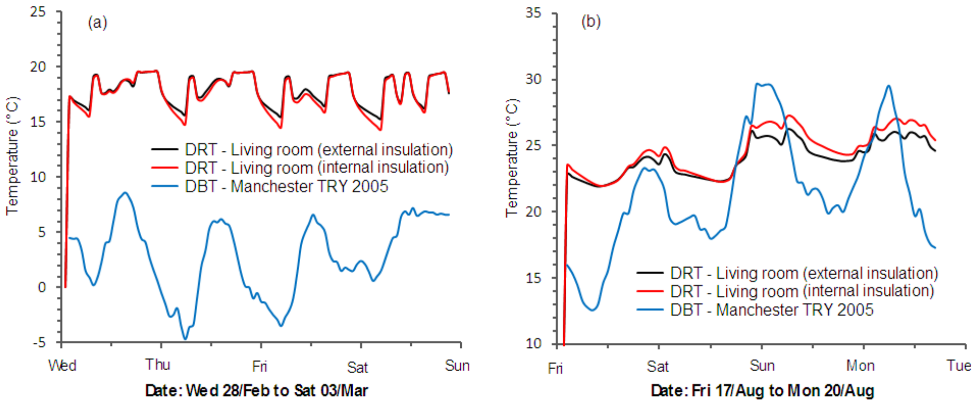


Figure 8. Living room DRTs at typical (a) cold winter days and (b) hot summer days.

Figure 9a shows the number of hours over temperatures between 22°C and 27°C for both living room and bedroom 1. If over 25°C is considered to be overheated the externally insulated construction performed significantly better than the internally insulated, with living room and bedroom 1 at 72 and 61 hours overheated respectively, compared with 111 and 151 hours for the internally insulated. For higher temperatures, i.e. over 26°C, the relative differences increase.

In Manchester, with its current relatively mild climate, overheating may not be a big concern for retrofitting at the moment but heavyweight construction does help to mitigate overheating. However, with potentially elevated temperatures in the future, this could be of increasing concern. As shown in figure 9b, the EH base case with the external insulation to 2010 Regulations level, the number of hours over 25°C, 26°C are going to get uncomfortably high, at some point before 2080. This potential concern should be addressed when retrofitting. It is worth noting that the indicative results shown here were generated using CIBSE TRY weather files. When considering overheating aspect of buildings, the CIBSE Design Summer Year (DSY) weather year should normally be used. The DSY was designed to represent the third hottest year in the past among the selected historical weather records. Simulating the EH model using projected DSYs will lead to much early warning of potential overheating. Using heavyweight construction will be beneficial but will not be sufficient enough, dedicated space cooling methods will need to be sought.

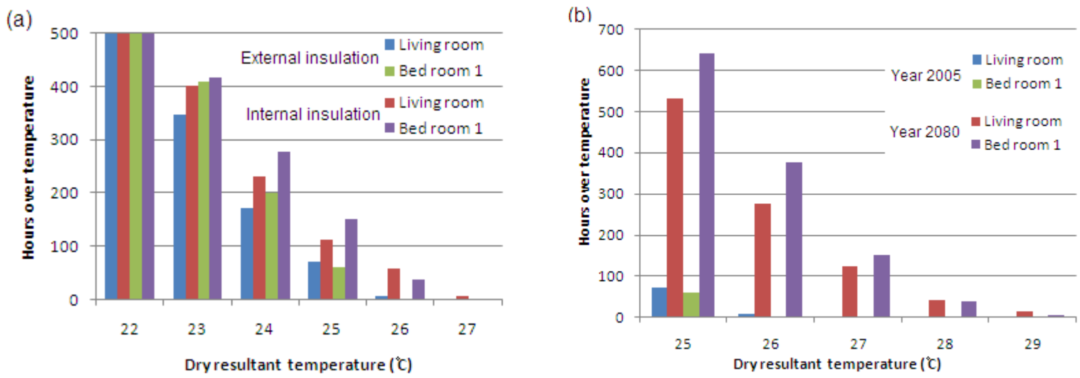


Figure 9. Accumulated number of hours over degree temperatures for the living room and bedroom 1, (a) with both internal and external insulations and (b) year 2005 and 2080 with external insulation only.

## 5 Conclusion and Further Research

This paper presents dynamic thermal simulations on a typical pre-1920s Victorian end terrace house with various retrofit options. The simulation results show that insulation, added either internally or externally, has a great potential to reduce space heating demands for this types of 'hard to treat' existing properties. With higher air tightness and the use of double-glazing, the overall saving on space heating demands can be as high as 60% when insulations on exposed walls and ceiling are at 2010 building regulations level. Thicker insulations result in more savings. However, when insulation thickness is increased to certain level, the benefits added are minor. Ventilation needs and other 'unchanged' constructions have dominant impacts on space heating energy demands when exposed walls are well insulated. Optimized insulation thickness needs to be balanced by these factors as well as the costs implications for materials and construction.

Even with the same thermal specifications for a building, space heating demands can vary significantly by occupants. As indicated by the simulation results, decreasing the heating set point by 2°C, the annual heating demands can be reduced by 20%. And if the house has a sensible heating cycle every day, rather than heated to set points all the time, the space heating demands can be further substantially reduced.

With increased levels of insulation and air tightness of new built or refurbished housing overheating may become a concern due to the likely elevated temperature in the future. This aspect was evaluated by using current and future TRY weather data. Although in Manchester, overheating may not be an immediate problem for domestic homes, in particular those with of heavyweight construction, the indicative results generated by the numerical model have shown that it is a concern for the future.

Future research will be looking at the costs of specific retrofitting measures and their implications for capital investment and payback time. These aspects are rather important, especially in the current economic climate, and retrofitting decisions will need to be justified.

## 6 Acknowledgement

The authors would like to thank the Energy hub manager - Steve Waterworth, the Energy house manager – Richard Fitton, for their technical supports on material specifications, and Dr William Swan, for initiating the Retrofit Symposium at Salford University.

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