International Journal of Building Pathology and Adap

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Journal:	*International Journal of Building Pathology and Adaptation*
Manuscript ID	IJBPA-12-2018-0106.R2
Manuscript Type:	Original Article
Keywords:	Retrofit, Energy Demand, Hard to Treat, Dynamic thermal Modelling, Energy House

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Abstract:

There is a clear consensus that improving energy efficiency of existing housing stock is necessary to meet the UK's legally binding carbon emission targets by 2050.The aim of this research is to assess the energy saving potentials from building retrofit using an end terrace house, similar houses represent about 30% of the existing building stock in the UK. The Salford Energy House - a unique pre-1919 Victorian end terrace house built within an environmental chamber was used. Retrofit modelling analysis was carried out using IESVE - a dynamic thermal simulation tool. The retrofitted model was also evaluated using future projected climate data (CIBSE latest release) to examine energy demands and overheating. Findings show that improving building fabric thermal characteristics can reduce space heating demands substantially. ~~Intermittent or constant heating~~Heating modes, set point preferences and infiltration level all have strong impact on heating demands. Space heating demand savings can be as much as 77% when the property facades were upgraded to the similar requirements of Passivhaus standards. The research implicates that, for dwelling retrofit practices, ~~A~~a whole house holistic approach ~~is~~ should be the preferred option to ~~maximize~~ improve energy efficiency. With future climate scenarios where temperatures are potentially elevated, the heating demands can be potentially reduced as much as 27%. The likelihood of overheating in dwellings after a deep retrofit due to future elevated temperatures becomes apparent. Therefore, mitigation of overheating risk becomes a necessity for future domestic housing stock retrofit planning and policy making. The research presented in this paper highlights the effectiveness of various retrofit measures individually as well as holistically, also the implications on energy demands and ~~of~~ the likelihood of overheating in dwellings under future climate scenarios.

Keywords:
Retrofit, Dynamic thermal Modelling, Hard to Treat, Energy Demand

1. Introduction

The argument for the sustainable refurbishment of the domestic sector in the UK is well documented [1-~~4~~6]. The domestic stock in the UK contributes to nearly 30% of UK carbon dioxide emissions [~~5~~7] and, with the UK replacing only 180,000 of its 27.3 million housing stock per annum [~~6~~8], it is clear that much of the stock that is currently standing will still be in-use by 2050 [~~7~~9, ~~8~~10]. The UK is committed to a reduction of carbon dioxide emissions, against 1990 levels, of 80% by 2050 as identified in the Climate Change Act 2008 [~~9~~11]. Much of the older stock has been constructed prior to Part L of the Building Regulations, which addresses energy efficiency issues, meaning that these properties are built to much lower or non-existent energy efficiency standards.

Given these issues, the sustainable retrofit of domestic properties is very much at the centre of debate. Domestic sustainable retrofit may be described as the upgrading of the fabric, systems or controls of a property to improve its energy performance. The UK Government has responded to this issue through the introduction of a number of policy initiatives, the Energy Company Obligation [~~10~~12], the Green Deal [~~11~~13], the Feed in Tariff [~~12~~14] and the Renewable Heat Incentive [~~13~~15], to improve the take up of retrofit measures in its housing stock, with a view to either reducing energy use or substituting low or zero carbon energy efficient measures. Sustainable retrofit is an essential part of the UK Governments carbon mitigation strategy, although its role in addressing both fuel poverty [~~14~~16] and, to some extent, energy security [~~15~~17], two other key energy policy objectives, should not be ignored.

Domestic sustainable retrofitting has been the subject of recent research given the need to reduce carbon emissions from building sector. With the 27.3 million housing stock and 90% of which will still be in-use by 2050, improving the housing stock energy efficiency through retrofitting is essential for the nation to meet its carbon reduction target. A number of studies investigated the feasibility of achieving deep cuts in carbon emissions from the housing sector as a whole by 2050, by generally using computer models of the whole stock [~~16~~18-~~18~~20]. The general consensus is that the 2050 target (80% carbon reduction against the 1990's baseline) is achievable providing a significant take up of the available retrofitting measures can be made sooner rather than later (i.e. efficiency measures on building fabric, hot water, efficient heating, controls, as well as large scale installation of renewable technologies). However, there are no easy, trouble free technological options at the moment. Additionally, many of the options are still yet to be cost effective, such as insulation for ground floor, renewable technologies [~~19~~21].

In terms of developing retrofit strategies, insulating the building fabric is common practice among construction professionals as a means of reducing heating demand. This fabric first approach is adopted as space heating consumes the majority of energy used in homes, with the energy being lost through the fabric via conduction and air infiltration. The Green Deal and the Energy Company Obligations both have insulation measures at their core, driving a fabric first philosophy that has emerged as part of UK retrofit practice [~~20~~22, 23]. Based on this policy driver and industry practice, we have considered fabric improvement as forming the backbone of any sustainable retrofit strategy for a 'Hard to Treat (HTT)' property type.

The Salford Energy House (SEH) facility is used in this research to demonstrate the effectiveness of various retrofit measures to address 2050 mitigation targets. SEH is a pre-1919 solid wall property and is of typical solid wall construction, as was used for houses built during the late 18th and early 19th centuries; these houses account to about 30% of the total stock and are regarded as HTT homes [24]. The Energy House model was initially validated using dynamic heat dissipation and the gas consumptions [~~21~~25], and further calibration of the model was also done using the co-heating tests [~~22~~26, ~~23~~27]. The previous validation and calibration studies provided creditable warrants for using the modelling approach to make informed retrofit decision making.

2. The Salford Energy House and its Model

SEH is a property that is constantly monitored in considerable detail and is located within an environmental chamber. It is a replica of a pre-1919's Victorian type, end-terrace house. The house was re-constructed using the contemporary construction technology at the time with reclaimed materials, for example, solid brick walls, lime mortar, lath and plaster ceilings, etc. In the past years, various tests were conducted using the facility – from full building retrofit to heating controls [~~22~~26, ~~25~~28]. SEH has become a hub for exploring domestic housing retrofit technologies. In Figure 1, the two images at the top show the rendered Revit model showing the spatial location of the house, and, the house surrounded by its chamber environment; the images below shows the floor plans of the house and its adjacent void. The environmental chamber is able to maintain steady indoor temperatures ranging from -12°C to 30°C with accuracy of ±0.5°C. It can also mimic conditions (with limitations) of rain, snow, wind and solar radiation. The use of SEH for fast track experimentation on various building retrofit technologies is one of its key advantages.

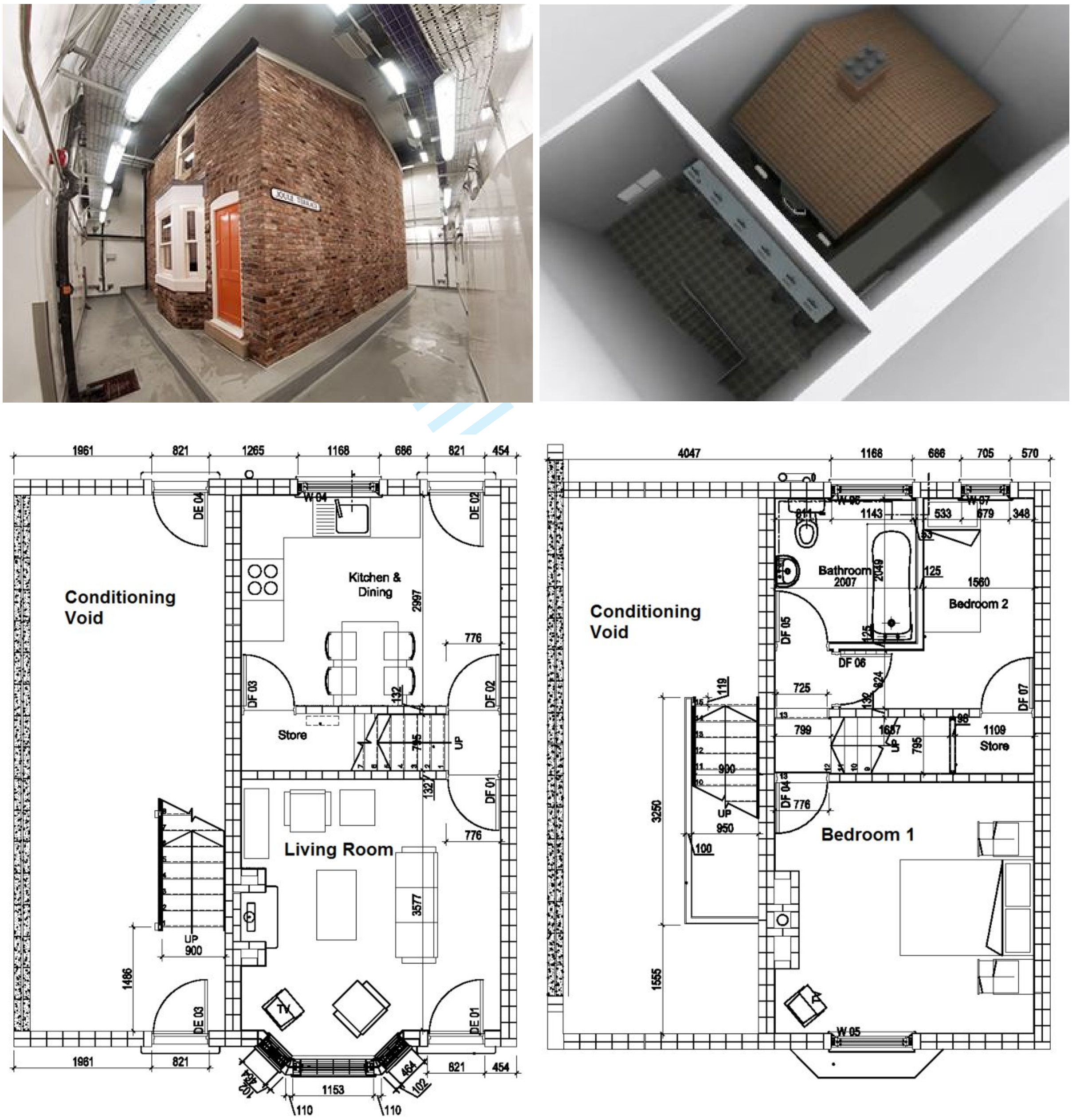

Figure 1 The Salford Energy House: The house with surrounding environment and rendered Revit model (upper images); ground and first floor plans (images below).

The dynamic thermal model of SEH is constructed using IES VE [~~26~~29]. IES VE is a well-established thermal simulation tool for analysing the dynamic responses of a building based on the hourly input of weather data. Figures 2 is the external view of the house model. The house compromises of a living room and a dining kitchen on the ground floor, and two-bedrooms on the first floor. The conditioning void replicates an adjacent environment to simulate a neighbouring dwelling to the end-terrace house. SEH is built on a cast concrete base, with vents provided for the raised timber ground floor. The fireplace is not in use due to the safety restriction of the testing environment within the laboratory. In the IESVE model, the chimneys were blocked due to this.

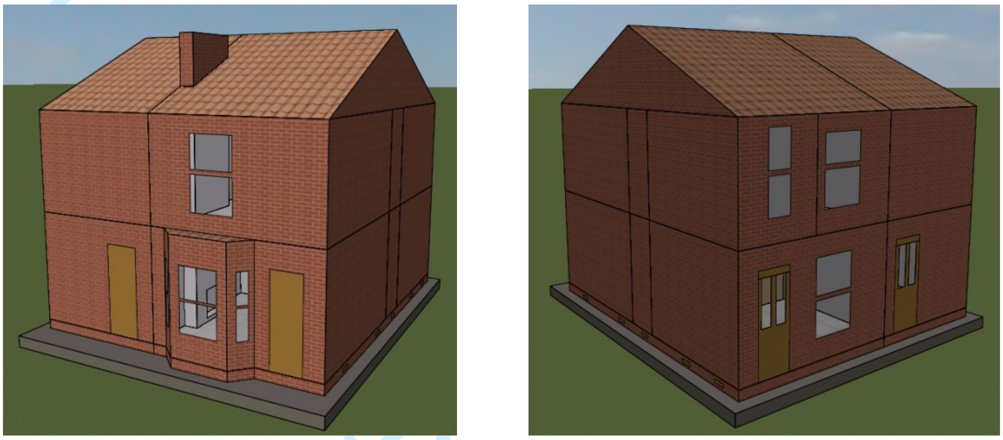

Figure 2 Axonometric view of the IESVE model of SEH, (a) front facade and (b) rear façade.

Table 1 shows the construction materials used for SEH. The reclaimed materials were used in order to make the testing facility as close as the pre-1919 Victorian terrace houses. The combined U-values of the given construction components/parts were calculated from the default thermal properties of individual materials.

Table 1 Construction details of SEH used in the modelling

Parts	Construction details	U-Values (W/m^{2}K)
External walls	Terrace house: 225mm brickwork + internal plastering; Condition void: 225mm brickwork + 45mm EPS Slab*	2.05 0.55
Partition walls	Internal – 13mm plastering + 115mm brickwork + 13mm plastering; Connection to Condition void – Plastering + 225mm brickwork	1.97 1.59
Ceiling/Floor	First floor: Synthetic Carpet + timber flooring + Cavity + Plaster First ceiling: Timber board + Glass-Fibre Quilt (100mm) + Cavity + Plaster	1.39 0.34
Roof	Slate Tiles + Felt/Bitumen Layers	6.45
Ground Floor	Synthetic Carpet + timber flooring + Cavity + Cast Concrete (dense)	1.53
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 detail is considered by mathematical representation (airflow through cracks) rather than 'drawing' them on the model physically. The rule of thumb is used 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. It is worth noting that tests were carried to measure the U-value of the external wall using a heat flux meter, the measured value was 1.88 (W/m^2K) rather than the calculated value (2.05 W/m^2K) from the given construction materials within the model (Table 1). This is not to say the calculated value is wrong. The measured value is taken from the average of a series of tests on different parts of the external wall. It was identified that the joints/edges, where cold bridging is likely to occur, had not been measured using this method, so the overall U-value of a wall may be more than the measured value. In the modelling exercise, the calculated U-value was used.

3. Modelling Considerations

The first stage of the modelling process is to use Salford Energy House, with the existing built quality, as a base model (BM). In the next stage, by varying parameters such as heating set points, insulation levels and background infiltration rates to evaluate the potential fabric heat loss and the energy demands for keeping the house at the required thermal conditions. For input data and assumptions discussed below, it is often arguable as to the level of simplification one has to make before a simulation is able to run. While some of data inputs and assumptions are indeed not directly representing the 'real cases' (i.e. occupancy profile, incidental gains, standard weather data, etc.), given a particular scenario, varying parameters relating to build quality and operation preferences would result in changes of energy demands for the building. These relative changes are very useful to indicate where the improvements can be made and how effective they are in terms of reducing energy demands for dwellings.

3.1 Occupancy and Heating Assumptions

a. Occupancy profiles

The house is assumed to be occupied by two working adults. Their daily life schedules are assumed and are shown in Figure 3. In reality, however, people are not going to experience their lives as repetitively as what is proposed; the way their lives are arranged is to make the modelling process more explicit and manageable. The schedules 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 appliances gains when they are present.

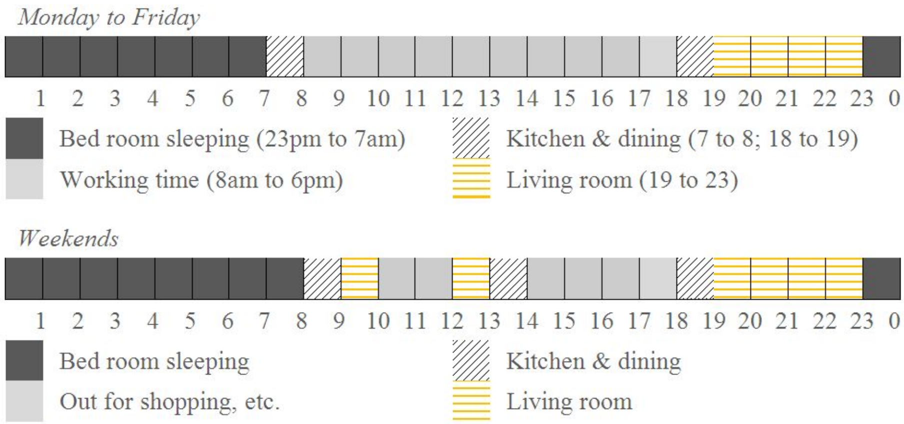

Figure 3 Schedules of the occupants (two working adults)

b. Heating set points and incidental gains

Relevant to the schedule profiles in Figure 3, from Monday to Friday, heating is scheduled 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/m^2 when needed, i.e. when occupants are in living room at night. 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) [~~27~~30]. 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 (maximum opening percentage for windows of living room, kitchen and bedroom 1 are 10%). SEH 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. This exercise is not part of the considered retrofit scenarios, but for gaining an understanding on the impacts of occupancy preference on the annual heating demands.

3.2 Retrofit Upgrade Assumptions

a. Energy loss through SEH facades and infiltration

Part of the space heating energy is used to heat up the cold infiltrated outside air to the desired temperature. The rest is for heating up the building fabric as well as balancing the heat losses through fabric. Exercises were carried out to evaluate the potential heat loss through individual building façades and infiltration under controlled conditions. This was done by firstly simulating SEH Base Model with the external chamber environment at 5°C, infiltration at 0.7ach and constant heating to 20°C internally for the terrace house, then to run the model progressively by making the following changes: no infiltration, then assigning adiabatic condition to the roof void, front façade, side façade, back façade and ground floor step by step. The differences between two immediate cases will reflect the heat losses relevant to the individual element that was made adiabatic, i.e. infiltration, roof void, front façade, etc.

Background infiltration for houses similar to SEH in real climate conditions could vary from 0.5 to 2.0 ach depending on the external environment and how well the house is maintained. 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 number of different infiltration rates were tested by the model to examine the amount of energy used due to infiltration ventilation only. The test infiltration rates are 2.0, 1.5, 1.0, 0.7, 0.5, 0.3 and 0 ach. This exercise will provide an implication on the ventilation associated energy demand under typical climate conditions, i.e. using the living schedule assumptions in section 3.1, heating to 20°C, and the Manchester Test Reference Year weather data (this will be explained further in section 3.3).

b. Fabric Improvements

The Salford Energy House is considered to be hard to treat (HTT) in terms of adding insulation due to its solid brick 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, or is subject to the restrictions of local councils if external cladding is to be considered. In the modelling, both internal and external insulation were tested individually to Building Regulation Part L1B level [~~28~~31]. 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 to prevent mould growth in buildings [~~29~~32]. 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.

3.3 Thermal comfort evaluation

An unintended consequence of building retrofit is the likely overheating after deep renovation [~~30~~33]. The dynamic thermal model of SEH was also evaluated using current and future projected weather data to examine the likelihood of overheating after retrofit.

The most recent release of weather data from CIBSE was in 2016 [~~31~~34]. Both Test Reference Years (TRYs) and Design Summer Years (DSYs) data were made available for 14 locations across the country: Belfast, Birmingham, Cardiff, Edinburgh, Glasgow, Leeds, London, Manchester, Newcastle, Norwich, Nottingham, Plymouth, Southampton, and Swindon. For average weather years (TRYs), the recent 2016 release is consistent with the former release in 2005 as the method used for selecting individual months for TRYs are essentially the same. Cumulative distribution functions (CDFs) of daily mean weather parameters were used to select candidate months of a test reference weather year. The three parameters used for typical weather year selection are Dry Bulb Temperature (DBT), Global Solar Radiation (GSR) and Wind Speed (WS). When generating CIBSE TRYs in 2005 release [~~32~~35], the average months were judged by the smallest Finkelstein-Schafer (FS) statistics (the sum of FS for the three parameters with equal weighting) by comparing CDFs of each individual month to the overall CDFs of the whole source weather parameters [~~33~~36]. In the latest 2016 release, the same statistical method was used. For the new release of TRYs, relative large variations were observed for some locations such as Norwich, Southampton and Swindon but these were largely attributed to the change of observation locations [~~34~~37]. The new metric used to select near extreme weather years for the DSYs in the 2016 release was 'weight cooling degree hours (WCDH). By definition, the WCDH metric assumes that the outdoor weather dry bulb temperature equals the indoor operative temperature. The metric not only accounts for overheating occurrences, but also gives emphasis overheating severity.

The retrofit modelling discussed in early sections used the Manchester Test Reference Year weather data. For consistency, Manchester probabilistic DSYs were used in this research to assess the likelihood of overheating. With the new release of CIBSE weather data, three probabilistic Design Summer Years (pDSYs) were produced in each location to represent different types of warm events, i.e. pDSY-1 represents a moderately warm summer; pDSY-2 has a more intense single warm spell; and pDSY-3 has a long period of persistent warmth. Higher WCDH leads to a longer return period, which indicates more severe summer warmth. For future climate scenarios, each of these pDSYs has three emission scenarios (low, medium & high [~~35~~38]) and for each emission scenario there are three probabilistic projections at 10, 50, and 90 percentiles. For the purpose of this research, we used Manchester future pDSY-3 weather projection 2020 (only high emission scenario available), 2050 & 2080 (medium emission scenario) at 50 percentile probabilities which represent a 'central estimate' [~~35~~38].

The adaptive overheating criteria from BS EN 15251 were used in this research [~~36~~39]. The limiting comfort temperature T_{comf} defined as BS EN 15251 by:

$$T_{comf} = 0.33Max(10,T_{rm}) + 18.8 \qquad \text{Eq. 01}$$

where,

$$T_{rm} = \alpha T_{rm-1} + (1-\alpha)T_{dm-1} \qquad \text{Eq. 02}$$

T_{rm-1} and T_{dm-1} are the running mean and daily mean temperature previous day, α is the constant between 0 to 1, here α = 0.8 as recommended by BS EN 15251. The limiting comfort temperature T_{comf}, as shown in Eq. 01, varies with the daily running mean temperature. The overheating limiting temperatures in BS EN 15251 were divided into three categories (Category I, II & III) and the upper and lower limit temperatures for these categories are shifted by 2°C, 3°C and 4°C, respectively, above and below the comfort temperature calculated using Eq. 01 (see Fig 11, where the comfort band and indoor operative temperature are presented).

4. Results and Discussion

The results discussed in this section primarily reflect the retrofit modelling exercises defined in sections 3.1 & 3.2, and the comfort evaluation focusing on potential overheating after retrofit using both current and future project weather data reviewed in section 3.3.

4.1 Energy demands verses heating set points

The annual energy demands (SEH Base Model, relative to 20°C set point) for space heating at various set points are shown in Figure 4. It is almost linear for the temperature range tested, and 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 close to 10%. The way how a house is heated also plays an important role in space heating energy consumption. The circle in Figure 4 represents the annual heating demands for the SEH Base Model at 20°C set point, but with the house constantly heated to the set point. This results in almost 50% increase in demand at the same set point when the house is heating intermittently (7 to 10 am and 6 to 11pm).

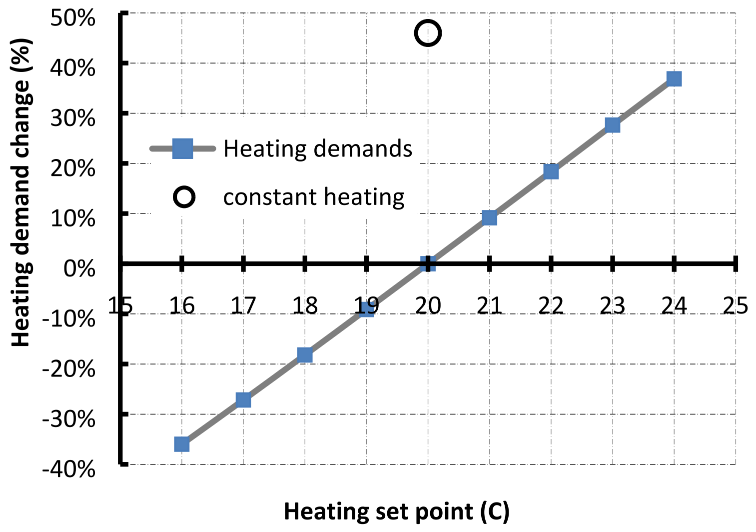

Figure 4. Space heating demands at various heating set points.

4.2 Heat losses through building facades and infiltration

Using the SEH Base Model and the scenarios detailed in section 3.2, the total amount of energy needed for the SEH is split into eight responsible elements, as shown in Figure 5. The percentages on the figure can also be viewed as the heat loss through each element for the given scenario. For this Base Model, about 15% of the energy is used to condition the infiltration air to the heating set point, and 5% of the total demand is lost through ceiling void (the Base Model has 100mm Glass Fibre Quilt insulation to reflect the as build condition of SEH). The Side Wall (ref: Figure 2) has a relative large exposed area, which is why it has the largest heat loss comparing other facades. The Front and Back Walls have relatively small exposed areas but they both have attached single glazed windows. Collectively, the vertical facades (side, front and back with their windows) are responsible for nearly 70% of the total heat loss. This exercise is to hightlight the importance of knowing where the heat losses occur and the relative heat loss portion they are responsible for. This is useful when making judgements on where the impovement should be applied and the likely saving may be obtained.

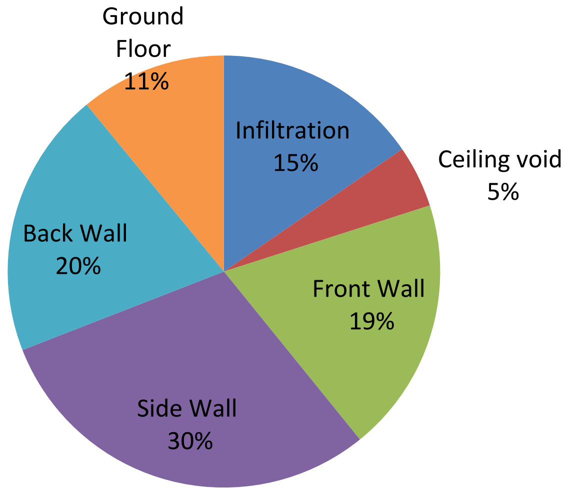

Fig 5 Relative heat losses through individual elements for SEH Base Model

Varying infiltration rates of the SEH Base Model affect heating demands needed due to the heating up of the infiltrated air to the desired temperature. When the SEH is modelled under standard weather condition and heating to 20°C set point (Figure 6a, also refer section 3.2), and when infiltration rate is at 0.7 ach, about 14% of the total space heating energy is used to warm the infiltrated outdoor air. It is worth noting that there is a slight difference in relative percentage heat loss from infiltration at 0.7 ach: 15% when the Base Model was under controlled condition (5°C chamber temperature and 20°C heating set point for the house, *ref*: Figure 5) verses 14% with the standard Manchester current TRY weather condition for the Base Model (Figure 6a). The two external conditions are obviously different, but relative heat loss to total, through infiltration, is almost the same. This indicates that the heat loss through infiltration is primarily determined by the physical state of the house, less relevant to its outdoor conditions. For more leaky conditions such as 2.0 ach, close to 40% of the heating energy is needed. The percentages here is relative to the SEH Base Model condition, if the hourse is improved to the minimum insulation required by Part L1B (2010) (*ref*: figure 7 in section 4.3), this percentage would be almost trippled, i.e. at 0.7 ach, about 40% of the total heating demand will be used to condition the infiltration air (see Figure 6b). This means that when dwellings are well insulated, heating up the fresh air supply to the desired thermal condition for occupants consumes a significant portion of energy. It is also worth noting that, infiltration rates lower than 0.5 ach during occupancy may be considered to be inadequate for fresh air supply. For newly 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 in case adjustment of fresh air is needed.

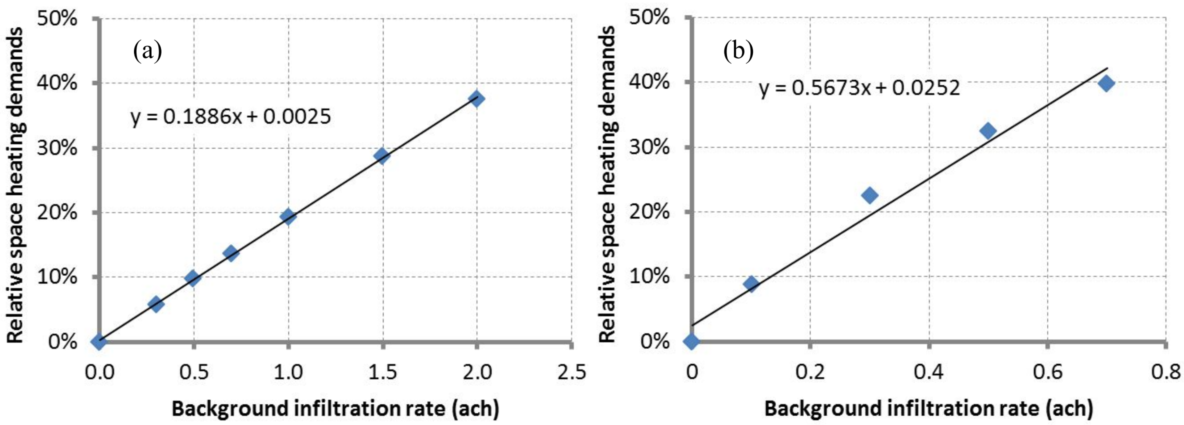

Figure 6. Relative space heating demands for various background infiltration rate, (a) SEH Base Model; (b) SEH is upgraded to Part L1B (2010) requirements

4.3 Heating demands verses various retrofit considerations

When testing internal insulations, Dense EPS Slab Insulation (Like Styrofoam) was added internally, also added a layer of plastering for the internal finishing (this is to avoid numerical instability at the internal surfaces). For external insulations, the required level of insulation was attached to the external brickwork. When insulating SEH to the minimum allowed insulation level of Building Regulation Part L 1B [~~28~~31], 58.5mm Dense EPS Slab Insulation is added for external wall and 134.5mm GLASS-FIBRE QUILT was added for the second floor loft space. The resulting U-values for the walls and roof are 0.35 and 0.25 W/m^{2}K respectively. The ground floor of the EH is a raised timber framed floor, above a concrete base. 84.0mm Dense EPS Slab insulation is added and the resulted U value is 0.25 W/m^{2}K. Figure 7 shows that around 50% of the original space heating demands are saved due to the added insulations to the exposed external walls, first floor ceiling and ground floor (improved to Part L 1B 2010 level); roughly another 10% energy saving for space heating can be realized by replacing single external glazing with standard low-e double glazing. Adding the influence from the potentially increased air tightness, the total reduction in energy demands for space heating is more than 65%. With space heating taking up nearly two-thirds of the total domestic energy usage, and nearly 30% of the total carbon emissions of the UK coming from domestic homes, reducing space heating energy consumption has great importance in meeting the nation's ambitious target to cut carbon emissions by 80% by 2050 against the 1990 baseline [~~19~~21]. Reducing heating demand also has practical benefits for individual home owners in terms of reducing heating bills.

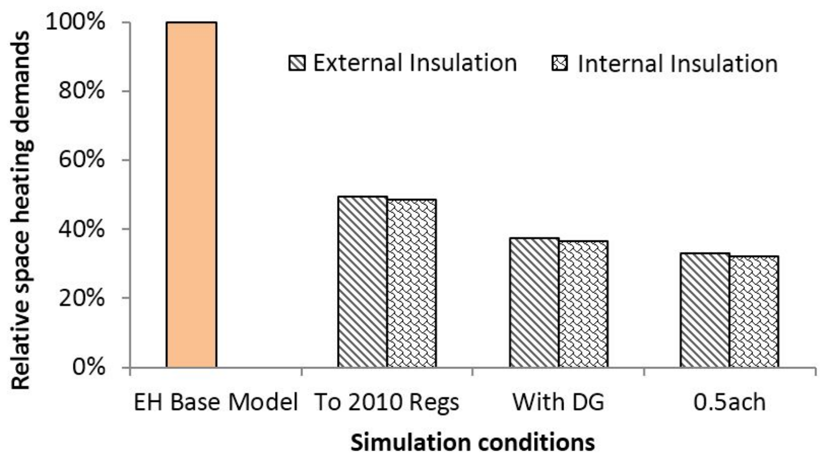

Figure 7 Comparisons between the EH base model, with insulation internally and externally, low-e double glazing and increased air tightness.

Figure 8a shows annual space heating demands for varying wall insulation thicknesses only, both internally and externally for the SEH Base Model. There is 100mm loft insulation for the base model but the ground floor is not insulated (in the case of concrete ground floor, it is often very difficult to add insulation). The thickness ranges given here are those commonly used by 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 40% compared with SEH Base Model (*ref.* Figure 7, the 100%); 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 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 putting them in place. Therefore, in practice, if more saving is expected, a holistic approach by improving insulation for all building fabrics would be more sensible than just focusing on one aspect of improvement. For example, Figure 8b, fabric improvement for Case I is to add insulations for loft (200mm), wall (100mm external) and ground floor (100mm), Case II is the same as Case I apart from adding the 100mm wall insulation internally, Case III is using double glazing and reduced air infiltration (0.5ach) on top of Case I, and Case IV is to extend the insulation thickness to 200mm for wall and ground floor on top of Case III. It is clearly seen that the relative large savings made from a holistic approach (i.e. Case IV) compared with merely increasing wall insulation to 200mm (figure 8a).

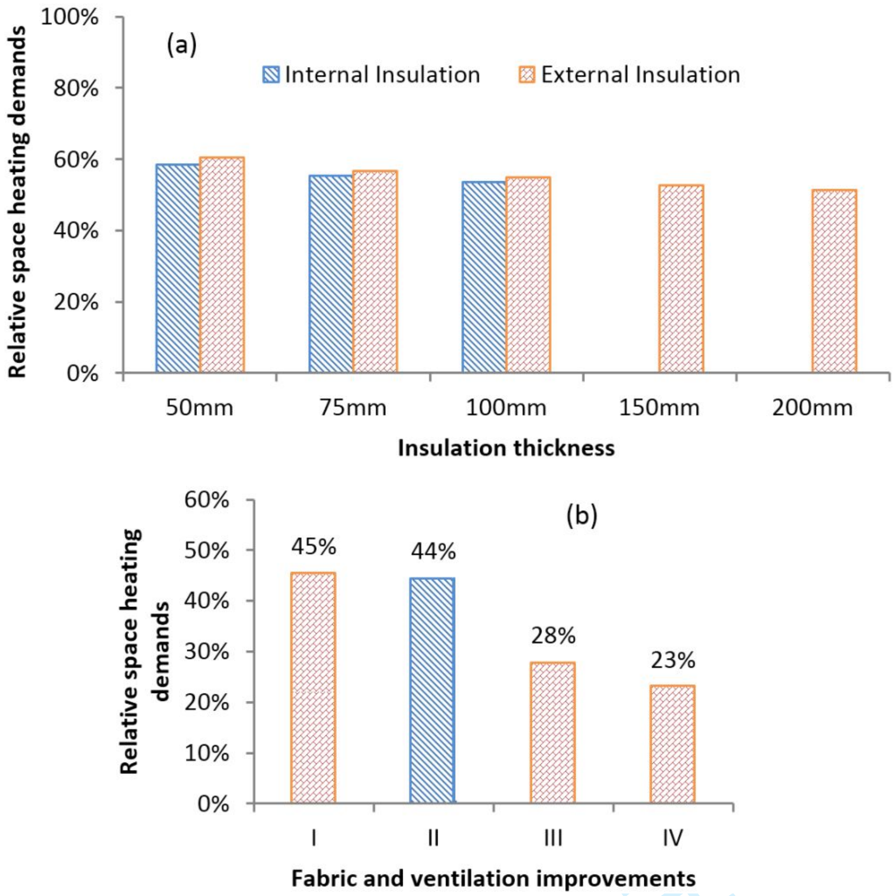

Figure 8. Annual space heating demands, (a) levels of insulation on exposed walls, (b) all around improvements

4.4 Thermal comfort evaluation

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.

Exposed thermal mass is much larger when adding insulation externally than when it is added internally for the SEH Base Model. As shown in Figure 8a (adding insulation externally and internally), when energy efficiency is concerned, the differences between the two are minor with the internal insulation option performing slightly better. Figure 9 shows the Operative Temperature in the living room during cold winter and hot summer weather using Manchester current TRY weather data. Operative Temperature variations with internal insulation are greater in both cases. This shows that heavyweight construction with exposed thermal mass (external insulation option) tends to be better in stabilising internal environment, with a lesser degree of oscillation compared with lightweight construction (when insulation is added internally). The resulting difference may be just up to 2°C, which does not seem to be a great deal, however, the accumulated effects can be important.

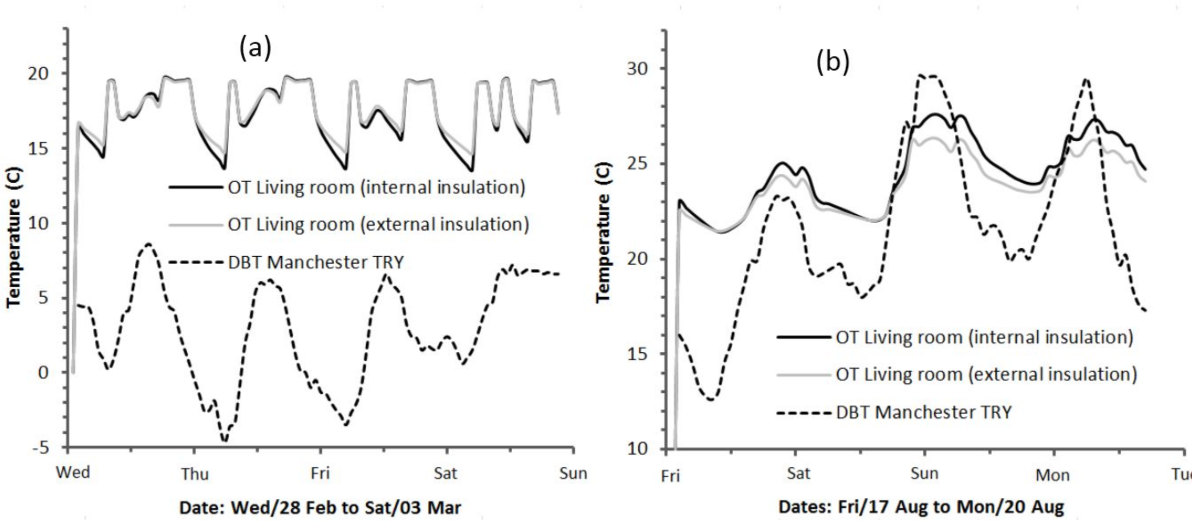

Figure 9 Living room DRTs at typical (a) cold winter days and (b) hot summer days using Manchester current TRY weather.

Figure 10 shows the number of hours over temperatures between 22°C and 27°C for both living room and bedroom 1. With the current Manchester TRY weather, the indoor temperatures in the two rooms are barely over 27C, which means overheating is currently not an issue. The differences between the internal insulation and external insulation are obvious with relatively higher temperatures, i.e. for over 25°C, the externally insulated construction performed significantly better than the internally insulated, with living room and bedroom 1 at 72 and 61 hours respectively, compared with 111 and 151 hours for the internally insulated. For higher temperatures, i.e. over 26°C, the relative differences increase.

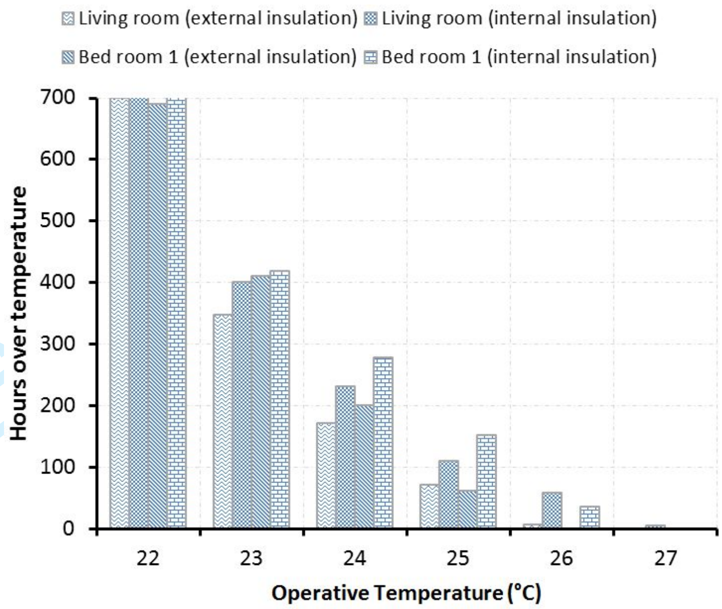

Figure 10 Accumulated number of hours over degree temperatures for the living room and bedroom 1 with both internal and external insulations

It is evident that heavyweight construction does help to mitigate overheating to some extent, and in Manchester, with its current relatively mild climate, overheating may not be a big concern for retrofitting at the moment. However, with potentially elevated temperatures in the future, this could be of increasing concern. Assuming a deep retrofit was done for the SEH, to the level of Case IV discussed in Figure 8b in section 4.3. The corresponding U-values for walls, ceiling (loft insulation), ground floor are 0.12, 0.18, 0.12 W/m^{2}K. Standard double glazing windows and the infiltration was assumed at 0.5 ach. The building fabric insulation level is similar as the requirements of the Passivhaus standard, but the house is not retrofitted to the standard holistically (the infiltration level and window U-values fall short in meeting the requirements) [~~37~~40]. This case was used for the potential overheating evaluation under future weather condition scenarios using the CIBSE latest weather data release as discussed in section 3.3.

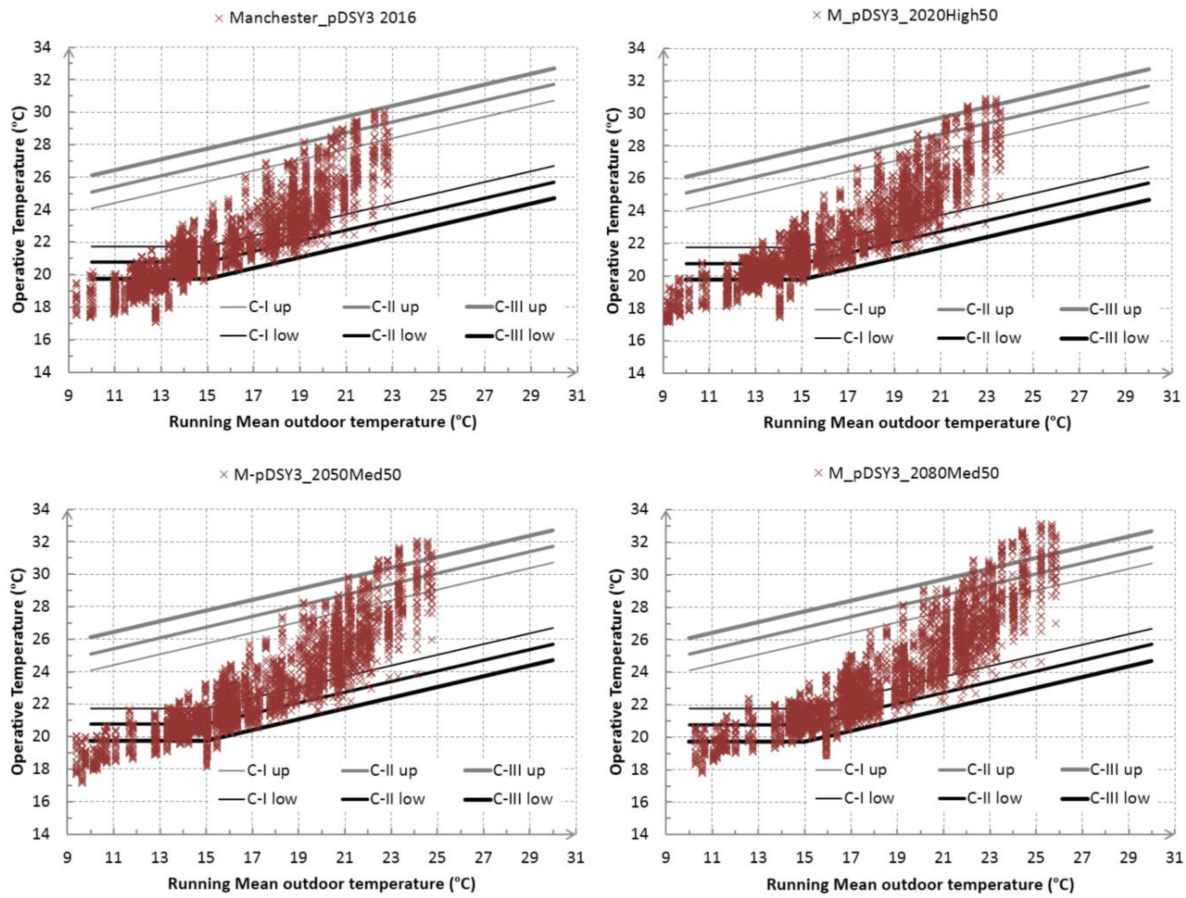

Figure 11 Indoor operative temperatures for the living room with current and future projected Manchester pDSY-3 weather data.

As shown in Figure 11, with the current DSY-3 weather data (the selected year for this current DSY is Manchester 1995), overheating in Summer (simulated period from May to September inclusive) is less of an issue as all the indoor operative temperatures are within the comfort range, no operative temperatures are above the category III ('C-III up' on the graph) upper limit. As described in BS EN 15251 [~~36~~39], Category I is the most stringent criterion with "*High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons*"; Category II is for "*Normal level of expectation and should be used for new buildings and renovations*", and Category III is for "*An acceptable, moderate level of expectation and may be used for existing buildings*". The case considered in this research is an existing building after a deep retrofit, Category III is appropriate for overheating consideration.

When using future projected DSY weather data, it is evident that overheating is likely to happen in the immediate future, i.e. by 2020 with a high emission scenario, there are some hours in summer the indoor operative temperatures are already above the Category III upper limit. And by 2050 and 2080, there are more indoor operative temperatures over the upper limit, indicating more severe overheating. There are also some operative temperatures below the Category III lower limit (C-III low) during the simulation period (May to September inclusive), more for the current DSY weather, less for the future project pDSYs. This is because the cooler days during summer time, without heating the indoor operative temperature can get outside the comfort bands.

The heating demands were evaluated with current and future elevated weather conditions using the case IV discussed in Figure 8 (the SEH underwent a deep retrofit). As shown in Figure 12, without doing anything extra, the heating demand will be reduced 27% by 2080 due to the elevated temperature in the future. Collectively, with the current climate condition, when the SEH was retrofitted to the level of case IV as discussed in section 4.3, 77% saving can be realized. If the outdoor temperatures are indeed elevated in the future to the extent discussed in this research, an 80% heating demand reduction (mirroring the government 80% carbon reduction targets) in the future is believed achievable.

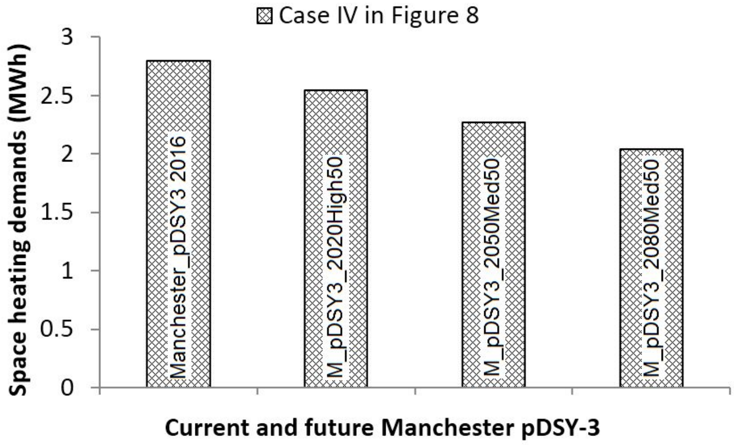

Figure 12. Heating demands for the deep retrofit case with current and future projected Manchester Design Summer Year weather data

5. Conclusions and discussions

This paper presents dynamic thermal simulations on a typical pre-1919 Victorian end terrace house with various retrofit options focusing on improving building fabric thermal performances. The simulation results show that insulation, added either internally or externally, has a great potential to reduce space heating demands for these 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 more than 50% when insulations on exposed walls, ceiling, and ground floor are at ~~2010~~ Part L building regulations 2010 level. Thicker insulation on external walls only will result in more energy savings. However, when the wall insulation thickness is increased beyond a certain level, the relative benefits and the amount of insulation added do not correlate well as other factors (such as windows, loft, ground floor and infiltration) become dominant in heat loss. Ventilation (through infiltration) ~~needs~~ and other 'unchanged' constructions can have strong impacts on space heating energy demands when exposed walls are well insulated. Therefore, it is important to know the shared responsibility of thermal loss through each individual façade element, so improvement can be proposed accordingly. For example, with the same amount of ventilation or infiltration, the amount of energy used to heat the house up to the required comfort temperature may be the same, but its shared percentage ~~over~~against the overall heating demands depends on how other façade elements perform. The research evidence highlights that a holistic approach is preferred when carrying out domestic housing retrofit. Optimized insulation thickness needs to be balanced by these factorsvarious other improvements of the whole house, as well as the costs implications for materials and construction practices. Improving the whole building insulation level similar to Passivhaus standards can reduce space-heating demand by as much as 77%.

Even with the same thermal specifications for a building, space-heating demand can vary significantly depending on how the building is heated (determined by occupant preference). As indicated by the simulation results, decreasing the heating set point by 2°C, the annual heating demands can be reduced about 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. This is one very influential aspect for the overall energy demand of a domestic house, unfortunately, also the one which cannot be fully addressed through improving the building fabric thermal conditions as it is down to the occupant's reference.

The overheating assessments for the house after a deep retrofit show that the likely overheating will indeed happen in the future although it is less of concerns at the current climate condition. Therefore, in future planning and retrofit policy making for dwellings mitigating the likelihood of overheating in the future becomes a necessity. Mitigation strategies, such as shading, forced ventilation, may be needed in the future in order to cope with the elevated summer warmth. With the elevated temperature in the future, one positive consequence is that the heating demand would be naturally reduced due to this, for the case considered in this research, as much as 27% of heating demands are reduced without any extra measures added to the retrofitted house.

The modelling exercises undertaken for this research is focused on the SEH, a typical Victorian end terence terrace house, within a well-controlled environment, the standard Manchester climate conditions and their future projections; the methodology used here can be applied to many other building types to investigate retrofit effectiveness, thermal comfort and overheating.

6. References

[1] Bell M. & Lowe R. (2000). "Building Regulation and Sustainable Housing. Part 2: Technical Issues." Structural Survey 18 (2):77-88

[2] Kelly, M. J. (2009). "Retrofitting the existing UK building stock." Building Research and Information, Vol. 37, No. 2, pp. 196–200

[3] Jenkins, D.P. (2010) "The value of retrofitting carbon-saving measures into fuel poor social housing", Energy Policy 38 pp 832–839

[4] Reeves, A., Taylor, S., Fleming, P (2010) "Modelling the potential to achieve deep carbon emission cuts in existing UK social housing: The case of Peabody", Energy Policy 36, pp 4241–4251

[5] William Swan, Richard Fitton, Luke Smith, Carl Abbott, Liz Smith, (2017) "Adoption of sustainable retrofit in UK social housing 2010-2015", International Journal of Building Pathology and Adaptation, Vol. 35 Issue: 5, pp.456-469, https://doi.org/10.1108/IJBPA-04-2017-0019

[6] Maria Rispoli, Samantha Organ, (2018) "The drivers and challenges of improving the energy efficiency performance of listed pre-1919 housing", International Journal of Building Pathology and Adaptation, https://doi.org/10.1108/IJBPA-09-2017-0037

[7] DECC (2011) Statistical Release. UK Climate Change Sustainable Development Indicator: 2010 Greenhouse Gas Emissions, Provisional Figures and 2009 Greenhouse Gas Emissions, Final Figures by Fuel Type and End user. Department of Energy & Climate Change.
[68] Palmer J & Cooper I (2012) "United Kingdom housing energy fact file", Department of Energy & Climate Change.
[79] Boardman, B (2007). "Examining the carbon agenda via the 40% House scenario", Building Research and Information. Vol. 35, iss. 4, pp. 363-378.
[810] Ravetz, J (2008). "State of the stock --What do we know about existing buildings and their future prospects?", Energy Policy, vol. 36, iss. 12, pp. 4462-4470.
[911] The Climate Change Act (2008). http://www.legislation.gov.uk/ukpga/2008/27/contents (Accessed: July 2018)
[1012] DECC (2010). Department of Energy and Climate Change: Energy Company Obligation – Carbon Saving Community Obligation. www.decc.gov.uk
[1113] DECC (2010). Department of Energy and Climate Change: The Green Deal – A summary of the Government's proposal. www.decc.gsi.gov.uk
[1214] FIT (Feed-in Tariffs): www.gov.uk/feed-in-tariffs/overview (Accessed: July 2018).
[1315] RHI (Renewable Heat Incentive): www.gov.uk/government/policies (Accessed: July 2018).
[1416] Hills, J. (2012). Getting the measure of fuel poverty: Final Report of the Fuel Poverty Review. London, United Kingdom.
[1517] DECC (2012). "Energy Security Strategy", Department of Energy & Climate Change, ISBN: 9780101846622
[1618] Boardman B. (2007). "Home Truths: A low-carbon strategy to reduce UK housing emission by 80% by 2050", University of Oxford's Environmental Change Institute.
[1719] Johnston D., Lowe R. & Bell M. (2005). "An exploration of the technical feasibility of achieving CO2 emission reductions in excess of 60% within the UK housing stock by the year 2050", Energy Policy, Vol 33, iss 13, pp 1643-1659.
[1820] Shorrock L D, Henderson J & Ultley J I (2005). "Reducing carbon emissions from the UK housing stock, Housing centre", BRE Environment
[1921] Killip G (2008). "Transforming the UK's Existing Housing Stock. Environmental Change Institute", University of Oxford.
[2022] Heaslip, M. (2012). "Low carbon housing for non-experts: usability in whole house retrofit". Retrofit 2012, Lowry, Salford, 24 – 26 January 2012, UK.
[2123] David Glew, Melanie B. Smith, Dominic Miles-Shenton, Christopher Gorse, (2017) "Assessing the quality of retrofits in solid wall dwellings", International Journal of Building Pathology and Adaptation, Vol. 35 Issue: 5, pp.501-518, https://doi.org/10.1108/IJBPA-05-2017-0022
[24] BRE (2008). "Energy Analysis Focus Report – A study of Hard to Treat Homes Using the English House Condition Survey". Building Research Establishment, UK
[25] Ji Y, Fitton R, Swan W, Webster P (2014). "Assessing overheating of the UK existing dwellings – A case study of replica Victorian end terrace house. Building & Environment", vol.77, pp. 1–11, doi: 10.1016/j.buildenv.2014.03.012
[2226] Farmer D, Gorse C, Swan W, Fitton R, Brooke-Peat M, Miles-Shenton D & Johnston D (2016). "Measuring thermal performance in steady-state conditions at each stage of full fabric retrofit to a solid wall dwelling", Energy & Buildings, vol. 156, pp.404-414, doi: 10.1016/j.enbuild.2017.09.086
[2327] Ji Y, Swan W, Fitton R & Marshall A. (2018). "Calibration of building dynamic thermal model using a unique whole house facility", Proceedings of the 17th International

Conference on Sustainable Energy Technologies, organized by: WSSET (World Society of Sustainable Energy Technologies), Hubei University of Technology, Wuhan, China, 21-23 August 2018

[~~25~~28] Fitton, R, Swan, W, Benjaber, MAA, Hughes, T and Todd, S (2016). “Assessing the performance of domestic heating controls in a whole house test facility”, Building Services Engineering Research and Technology, vol. 37, iss. 5, pp. 539-554.

[~~26~~29] IES VE Version 2017, Integrated Environmental Solutions Virtual Environment, www.iesve.com (accessed: 20/02/2018).

[~~27~~30] Stephen, R.K. (1998). “Airtightness in UK dwellings: BRE’s test results and their significance”, Building Research Establishment, BRE359, UK.

[~~28~~31] Building Regulations (2010). “Approved Document L1B – Conservation of Fuel and Power in Existing Dwellings”, ISBN: 9780117068483.

[~~29~~32] Ridley, I., Mumovic, M., Davies, M., and Oreszczyn, T. (2006). “Building Research Technical Report 8 - Impact of Replacement Windows on IAQ of Occupied Dwellings Project”, The Bartlett School of Graduate Studies, University College London, for Office of the Deputy Prime Minister

[~~30~~33] Mavrogianni, A; Davies, M; Taylor, J; Oikonomou, E; Raslan, R; Biddulph, P; Das, P; Jones, B; Shrubsole, C (2013). “The unintended consequences of energy efficient retrofit on indoor air pollution and overheating risk in a typical Edwardian mid-terraced house”, FutureBuild - International Conference, 04 - 06 September 2013, University of Bath, UK.

[~~31~~34] Virk D & Eames M (2016). “CIBSE Weather Files 2016 release: Technical Briefing and Testing”, https://www.cibse.org/getmedia/ce7a77e8-3f98-4b97-9dbc-7baf0062f6c6/WeatherData_TechnicalBriefingandTesting_Final.pdf.aspx (accessed July 2018)

[~~32~~35] Levermore G & Parkinson J (2006). “Analyses and algorithms for new Test Reference Years and Design Summer Years for the UK”, Building Service Engineering Research & Technology, vol 27, pp. 311–325.

[~~33~~36] Ji, Y., Korolija, I. & Zhang, Y. (2018). “Thermal responses of single zone offices on existing near-extreme summer weather data”, Journal of Building Simulation, Volume 11, Issue 1, pp 15–35, https://doi.org/10.1007/s12273-017-0367-y

[~~34~~37] Eames M (2016). “An update of the UK’s design summer years: Probabilistic design summer years for enhanced overheating risk analysis in building design”, Building Services Engineering Research and Technology, vol.37, pp. 503–522

[~~35~~38] UKCP09 Annex 1 – The UK Climate Projections 2009 - Emissions scenarios used in UK Climate Projections Science Report. https://arcc.ouce.ox.ac.uk/wp-content/D4FC/06-appendix1-Bill-Gething-CCreport-0510.pdf (Accessed: 20 June 2018)

[~~36~~39] BS EN 15251 (2007). “Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics”, BSI, EN 15251:2007 (E).

[~~37~~30] Schiano-Phan, R.; Ford, B.; Gillott, M.; Rodrigues, L. (2008). “The passivhaus standard in the UK: Is it desirable? Is it achievable?”, In Proceedings of the 25th Conference on Passive and Low Energy Architecture, Dublin, UK, 22–24 October 2008