LEEDS BECKETT UNIVERSITY
LEEDS SUSTAINABILITY INSTITUTE

Wikihouse

Thermal Performance Modelling & Life Cycle Assessment

Innovate UK Project number: 77084

Contents

Executive Summary

There is a balance to be achieved between operational carbon dioxide (CO_2) emissions, construction costs and Life Cycle Assessment (LCA) when designing any building. This report evaluates the operational and embodied CO_2 of the Wikihouse Skylark design; the cost of construction is outside of this report's scope.

The first section of this report (2.1) presents the results from a sensitivity analysis (SA) which quantifies the impact of three different variables on the thermal performance of the building. Variables considered include: four insulation products; four window types; and five levels of airtightness. The SA was designed to provide the Wikihouse design team with quantified data on which to base their selection of materials. The Heat Transfer Coefficient (HTC) of a dwelling quantifies the overall fabric performance independent of any differences in occupancy, heating systems or site location. The results from the SA show that the Wikihouse Skylark system can achieve similar HTC values as those in dwellings built to the Passivhaus standard when using triple glazing and the lowest airtightness targets. Results also show that, when using the better performing insulation products and lower airtightness targets, the use of triple glazed units as opposed to high-performance double glazing as a relatively low impact on annual heating costs. Based upon the SA, the Wikihouse team specified the use of an insulation product made from recycled material and an airtightness target of 0.15 air changes per hour for the target performance of the Skylark system. Very low background infiltration rates can be difficult to attain in practice and the rate 0.15 was selected to ensure the target was practical in reality.

Once target performance values were identified through the SA, these were then used to model the annual energy and CO_2 of two-bedroom designs for a two-storey house and a bungalow (section 2.2). To align with Real Living Homes' initial area of development, the majority of this analysis focused on models using simulation weather files for the Leeds area. However, the dwellings were also modelled in other locations and in different orientations around the UK. Results show that the Wikihouse Skylark design would achieve considerable savings when compared to notional dwellings with fabric standards that meet the minimum required by Part L1A of the Building regulations. When compared to the notional design, the two-bedroom house with double glazing would achieve annual savings of approximately 2,200 kWh (equivalent to £310 in utility costs and 300 $kgCO_2$); with triple glazing this increases to 2,500 kWh (equivalent to £350 in utility costs and 350 $kgCO_2$). For the bungalow design, the absolute value of these savings increases to 2,500 kWh (£350/340 $kgCO_2$) for the double-glazed building and 2,700 kWh (£380/370 $kgCO_2$) when using triple glazing. The final section of the target performance analysis (section 2.3) evaluated the potential for overheating in the proposed designs. Whilst the house and bungalow could easily mitigate against excessive overheating in Leeds under current and future climate scenarios, it would be necessary to consider additional mitigation measures if building in locations susceptible to more intense heatwaves. A central London location was used to help illustrate performance under these much more intense conditions.

An LCA analysis showed that the Wikihouse had less than half the life cycle greenhouse gas (CO_{2eq}) emissions of a conventional brick and block cavity wall house (built to the same fabric standards as the Wikihouse target performance values), when considering a 100-year assessment period. This result was achieved because of the carbon stored in timber products is assumed to be carbon negative over the assessment period. It was also influenced by the carbon intensity of more heavyweight building materials and traditional mineral wool insulation. However, this difference would be much less pronounced if the Wikihouse design was used to produce a dwelling that met minimum fabric standards defined within Part

L1A. In this scenario, the operational emissions are reduced by approximately 3,000 $kgCO_{2eq}$ over the 100-year LCA period. This further emphasises the importance of the embodied carbon within traditional building materials, which would be even more significant if potential reductions in the electricity grid carbon intensity are achieved. The forecast decarbonisation of the UK national grid reduced the contribution of operational energy in the LCA, representing around 60% and 25% of emissions of the Wikihouse and conventional brick and block low energy house respectively. This finding implies that in order to reduce life cycle impacts of low energy homes, more focus should be paid to the embodied emissions in building materials, rather than striving for net zero carbon operational emissions. This has important implications for future policy development in this sector.

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July 2021
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1.0 Introduction

Life time operational energy consumption often accounts for the greatest proportion of carbon dioxide (CO_2) emissions in traditional buildings; this is however, less definitive in low-energy dwellings, such as Passivhaus buildings [1]. As part of the Innovate UK funded project "Transforming local supply chains for zero carbon homes" Leeds Beckett University have evaluated both the forecast operational CO_2 emissions of the Wikihouse 'Skylark' timber frame system and the embodied CO_2 through Life Cycle Assessment.

The Leeds Beckett University research for the Wikihouse buildings is divided into two main sections: the first aspect of the work models the thermal performance of the Wikihouse Skylark buildings in the context of fabric heat loss, operational energy and CO_2 emissions, and thermal comfort, with a specific focus on the potential for overheating. Outputs from the thermal performance modelling are then used in section 2.0 to inform the Life Cycle Assessment (LCA) which quantifies the CO_2 emission from cradle to grave.

2.0 Thermal Performance Modelling

This section of the report describes the thermal performance analysis. The first stage of this work focused on a sensitivity analysis to quantify the operational energy consumption, costs and CO_2 emissions using different types of insulation materials, different glazing options and a range of infiltration rates. This allowed the Wikihouse design team to select target performance values to be used in the subsequent modelling of annual energy use. As the Wikihouse Skylark systems is essential lightweight in terms of thermal mass, the final aspect of the modelling focused on the potential for overheating in current and future climate scenarios.

All of the models included in this work were produced using the DesignBuilder dynamic thermal simulation software which uses the open source Energy+ software as its physics engine [2]. This software is independently validated and approved for use in dynamic thermal simulation analysis by chartered engineering organisations [3, 4]. Dynamic simulation software is defined by the ability to model at least 8,760 time steps i.e. each hour of an annual period. The software therefore, requires building simulation weather files with hourly resolution input data; all of the weather files used in this work are published by the Chartered Institute of Building Services Engineers [5].

2.1 Fabric sensitivity analysis

As noted above, the first stage of this work focused on a fabric sensitivity analysis. The two-bedroom detached house design was used as a basis for this work orientated North-South, with the front door facing the South. An image and plan layout of the two-bedroom house is shown in Figure 2.1. For the fabric sensitivity analysis and baseline annual simulations, the CIBSE Test Reference Year (TRY) weather file for Leeds was used, to provide a market context for Real Living Homes [5]. These TRY inputs are the most common type of weather file and are created to represent typical conditions using observed data, either by using a twelve month period considered representative of average conditions, or a composite file of typical individual months (as is the case for the UK) [6].

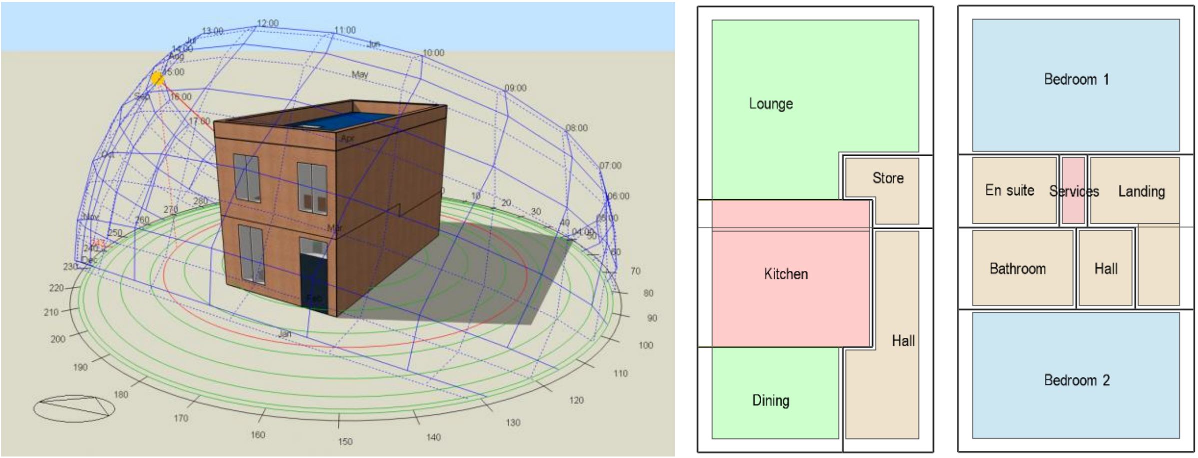


Fig. 2.1 Model geometry and floor plans for Wikihouse Skylark two-bedroom detached house

The primary metric used to compare the performance of each model variant is the Heat Transfer Coefficient (HTC) which is expressed using the units Watts per Kelvin (W/K). The HTC describes the conductive heat losses through the fabric and the convective heat losses that are result of infiltration (and not intended ventilation) [7]. This metric is independent of the building systems and is calculated by creating a model that mimics a coheating test [8, 9]. The coheating test is modelled by adjusting inputs to reflect the real test conditions, with no internal heat gains from people, lighting and equipment included in the simulation. A convective electric heat source with a performance coefficient of 1.0 is specified to model the required heat input. Heating set points were specified as constantly running at 25°C [10]. Outputs from the model can then be used to calculate the HTC. Analysis of real coheating test data removes the influence of solar gains through linear regression and this technique is replicated using the model outputs. The power output is used as the dependant variable and results are regressed using the mean daily global solar and the difference between indoor and outdoor dry bulb temperature (ΔT) as the independent variables. Through Analysis of Variance (ANOVA), a coefficient is calculated and used to multiply the mean daily solar values before they are summed to calculate the power used to maintain the internal temperature that simulates the coheating test conditions.

In layman's terms, the HTC can be thought of in a similar way as the miles per gallon (MPG) metric used to describe the efficiency of cars; the coheating conditions heat the home continually for at least two weeks at 25 °C. The amount of power required to maintain this temperature can then be compared to the difference between indoor and outdoor temperature to calculate the W/K result. As with the MPG value for cars, the efficiency of the car in practice is dependent upon the use of the car. The performance of homes is also dependent upon how they are used but the HTC W/K figure provides a fixed metric that can be used to fairly compare one home with another.

The variables used the sensitivity analysis were insulation types (four options), window types (four options) and the background infiltration rate (five options). A total of 80 model runs were therefore, required to compare every possible combination of these three variables. Links to the different insulation and window options are provided below in Table 2.1, the background infiltration rates used were expressed in air changes per hour and included 0.5, 0.25, 0.2, 0.1 and 0.05 (0.5 being the minimum required for new-build housing and 0.05 being close to the 0.03 rate required for certified Passivhaus dwellings) [11, 12]. These variables were agreed with the Wikihouse design team prior to the analysis.

Table 2.1 Fabric sensitivity analysis model input variables

Variable:	Technical value:
Insulation material:	
https://www.knaufinsulation.co.uk/products/loft-roll-44	Conductivity = 0.044 W/m·K
https://www.ecomerchant.co.uk/walls/insulation/thermafleece-range/supasoft.html	Conductivity = 0.040 W/m·K
https://www.indinature.co/specifications	Conductivity = 0.044 W/m·K
https://naturalinsulations.co.uk/product/cosywool-rolls/	Conductivity = 0.039 W/m·K
Window units:	
https://www.kingfisherwindows.co.uk/aluminium/	U-value = 1.50 W/m^2·K
https://idealcombi.com/windows/contemporary-windows/	U-value = 1.31 W/m^2·K
https://www.greenbuildingstore.co.uk/alu-clad/	U-value = 0.85 W/m^2·K
http://www.leedswindowcentre.co.uk/windows	U-value = 0.80 W/m^2·K
Background infiltration:	
Air changes per hour (AC/H) 0.50	10 AC/H @ 50 Pa
0.25 AC/H	5 AC/H @ 50 Pa
0.20 AC/H	4 AC/H @ 50 Pa
0.15 AC/H	3 AC/H @ 50 Pa
0.10 AC/H	2 AC/H @ 50 Pa
0.05 AC/H	1 AC/H @ 50 Pa

The insulation types were used in the plane element constructions for walls, roof, and ground floor. Each material resulted in a different overall U-value for the element and these are listed in Table 2.2. To provide an accurate representation of the U-value that would be achieved in reality, it is important to include the effect of repeat thermal bridging (caused by structural timber that bridges the insulation inside the plane element) within the plane element; the calculated U-values for the constructions before and after the repeat bridging is accounted for are noted in Table 2.2. Open Systems Lab calculated the percentage of repeat thermal bridging in the typical elements to be 5.82%. Repeat bridging differs from the linear thermal bridging which occurs at junctions between building elements. The linear thermal bridges are also included in the models, using Psi (Ψ) values expressed in W/m·K. The Ψ values are listed in Table 2.3; it is important to note that these are based upon values provided by Open Systems Lab for an earlier version of Wikihouse and should be calculated based upon detailed design for any proposed developments in future.

Table 2.2 Plane element U-values using alternative insulation types

	Without repeat bridging			With repeat bridging		
Insulation product	Walls (W/m^2·K)	Roof (W/m^2·K)	Floor (W/m^2·K)	Walls (W/m^2·K)	Roof (W/m^2·K)	Floor (W/m^2·K)
Knauf	0.158	0.146	0.142	0.176	0.161	0.156
SupaSoft	0.145	0.134	0.131	0.164	0.15	0.146
IndiTherm	0.139	0.127	0.125	0.158	0.144	0.141
Thermafleece	0.142	0.131	0.128	0.161	0.147	0.144

Table 2.3 Linear thermal bridging Psi values used in all models

Junction:	Psi (Ψ) value
Roof-Wall	0.079 W/m˙K
Wall-Ground Floor	0.079 W/m˙K
Wall-Wall	0.047 W/m˙K
Wall-Intermediate Floor	0.001 W/m˙K
Lintel (above windows & doors)	0.038 W/m˙K
Sill (below windows & doors)	0.038 W/m˙K
Jamb (around windows & doors)	0.021 W/m˙K

In addition to using the HTC as a quantifying metric, the modelled energy consumption and associated cost have been used to interpret the performance of the proposed designs. Annual simulations are used to achieve this, and these require a further set of model inputs. These include: occupancy patterns and associated internal heat gains (from people, lighting, and equipment); heating and cooling set points; and Heating, Ventilation and Air Conditioning (HVAC) system performance details. The occupancy profiles and associated heat gains used in these models are based upon those used in the UK's Standard Assessment Procedure (SAP) [13] and the National Calculation Method (NCM) [14]. It is however, important to note that dynamic thermal simulations operate at hourly time-steps whereas steady-state models, such as SAP, use aggregated daily values to calculate the overall heat balance; dynamic models therefore, require a much higher resolution of input data. The NCM database is used in dynamic modelling of non-domestic buildings but does include inputs for residential properties, hence using both sources in these models. For further reading, a comparison of dynamic and steady-state models can be found in this report [15]. The chart in Figure 2.2 illustrates the typical occupancy pattern assumed in SAP, with a typical family out at work and school during weekdays.

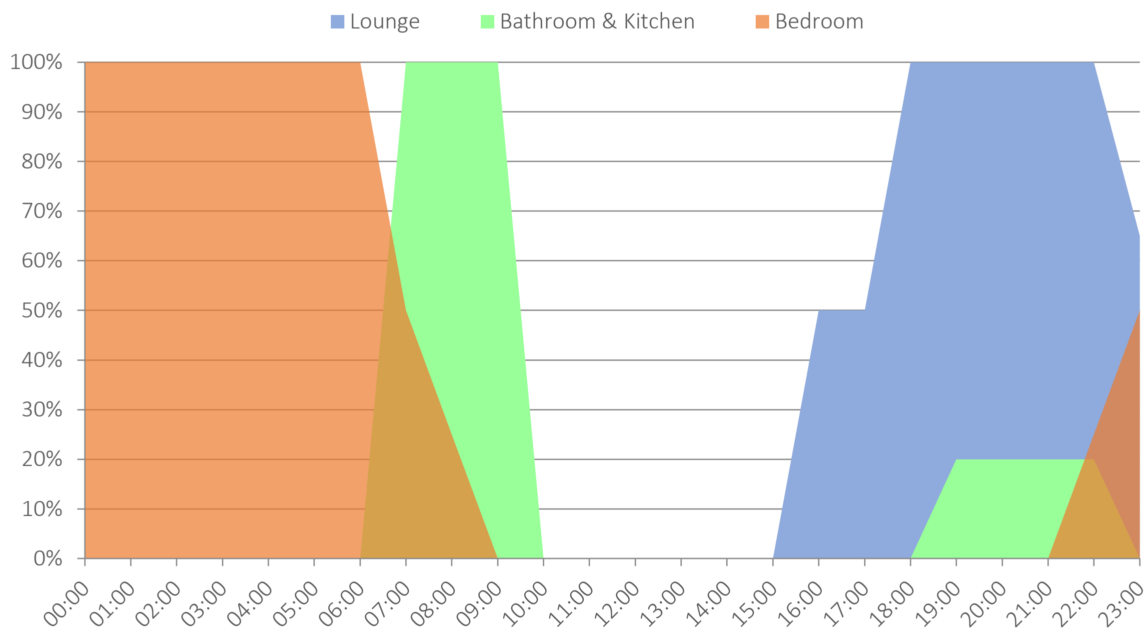


Fig. 2.2 Typical occupancy profiles assumed in SAP

There is currently no approved regulatory compliance approach for dynamic modelling in the UK, hence the need to take a hybrid approach to the energy modelling described in this report. As noted above, the occupancy schedules align with those described in SAP but this aggregates daily values. Therefore, the hourly data described in the NCM are used for the heat gains from people and equipment; these are noted in Table 2.4. In addition to these inputs, it has been assumed that the Wikihouse will use LED lighting (with a power density of 7.5 W/m^2) with a daylighting control function during occupied periods. The HVAC system inputs were agreed with Open Systems Lab prior to modelling and include a simple radiant electric heating system with a coefficient of performance of 1.0 and a Mechanical Ventilation and Heat Recovery (MVHR) system to provide the purpose fed ventilation. The MVHR system is set to deliver 0.6 AC/H, with an 80% efficient heat recovery rate and a constant power demand of 0.26 W/m^2. The heating set point in living areas is a constant 21 °C and in all other areas a constant 19 °C. Whilst these environmental controls differ from those normally used in SAP calculations, they align with the conditions assumed in Passivhaus PHPP modelling [12]. It is, however, important to note that PHPP is also a steady-state calculation and assumes lower internal heat gains than SAP or the NCM.

Table 2.4 NCM default inputs for heat gains in different zone types in dwellings

Zone	People (W/m^2)	Lighting (W/m^2)	Equipment (W/m^2)
Bathroom	120	3.75	1.67
Bedroom	90	2.50	3.58
Circulation	180	2.50	1.57
Dining area	110	3.75	3.06
Kitchen	160	7.50	30.28
Lounge	110	3.75	3.90
Toilet	140	2.50	1.61

2.1.1 Sensitivity analysis results

Heat transfer coefficients for the model variants are shown in Figure 2.3 and have been plotted against the modelled annual heating cost (based upon an electricity cost of 14p/kWh [16]). To a certain extent, the results are intuitive, as the products with the better performance values achieve the lowest HTC results and the lowest annual heating cost. Although the cost of materials was not within the scope of the thermal modelling, it is an important consideration in the development of the Wikihouse design overall. It is also especially important within the context of this Innovate UK project and for Real Living Homes, who aim to deliver high quality affordable homes in the social housing sector. Quantifying the potential performance of all of these model variants therefore, allowed the design team to identify a level of performance that would create a balance between low annual utility costs and affordable materials. The results from the sensitivity analysis emphasised the importance in achieving low infiltration rates in this type of low-energy design, particularly as MVHR will be used in these dwellings. The need to achieve good levels of airtightness when using MVHR systems is well established in the literature [17, 18].

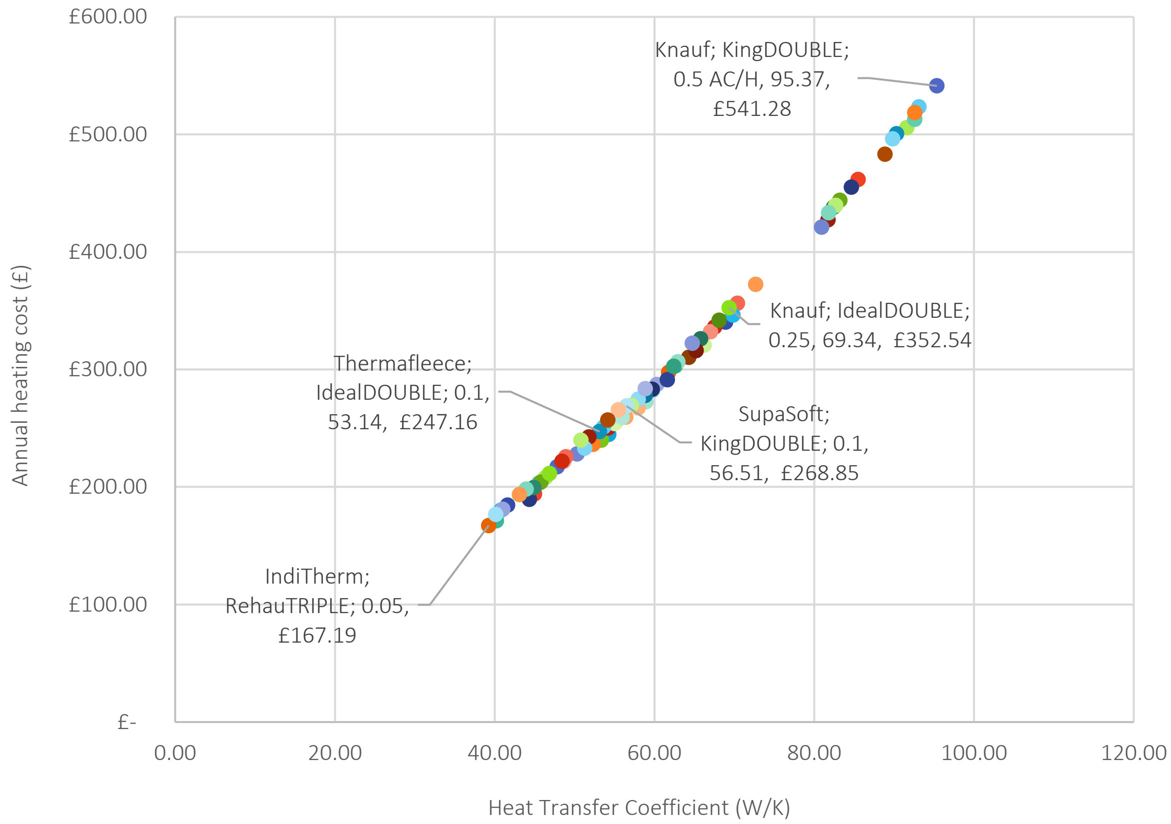


Fig. 2.3 Modelled HTC and annual heating cost from sensitivity analysis

As part of the HTC calculation, it is possible to disaggregate the heat loss between the heat losses from the building fabric, the linear thermal bridging and the losses from infiltration. A breakdown of these values is shown in Figure 2.4 for the model variants using an infiltration rate of 0.1 AC/H.

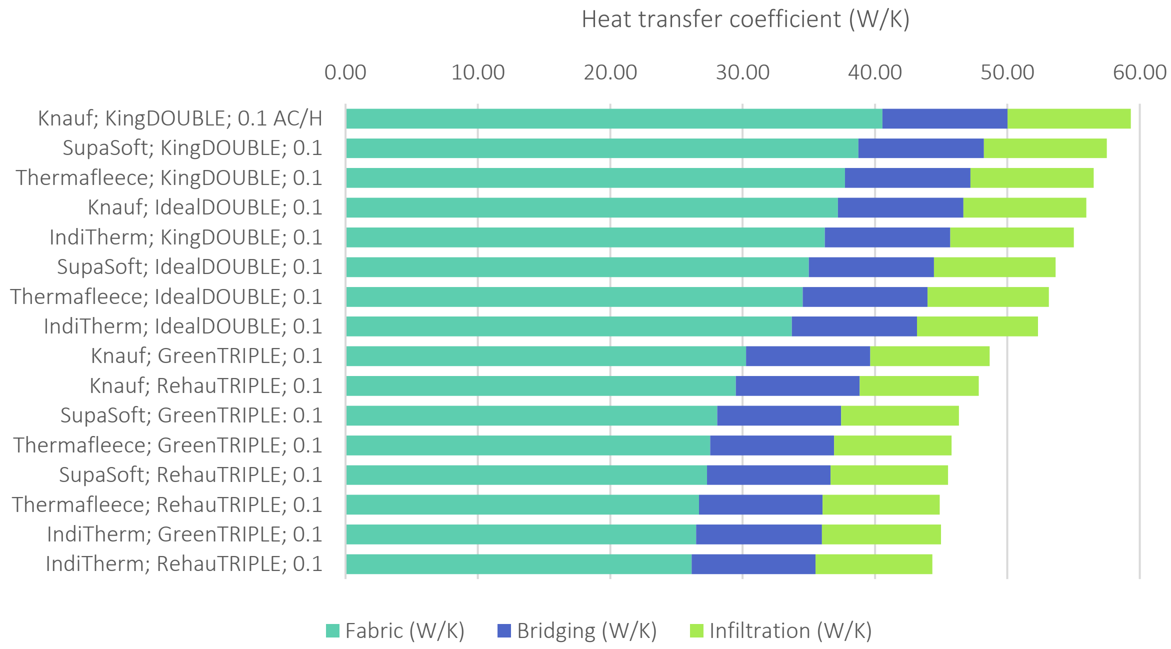


Fig. 2.4 Modelled HTC for fabric, linear bridging and infiltration

As can be seen in Figure 2.4, there is a step down in energy cost when switching from double glazed units to triple glazed units. However, the better performing models using double glazing achieve a similar performance to the worst performing triple glazed versions. This is mirrored by the annual heating costs which are shown in Figure 2.5, with a saving on annual heating costs of approximately £24 between the best performing double glazed version and the worst performing triple glazed version.

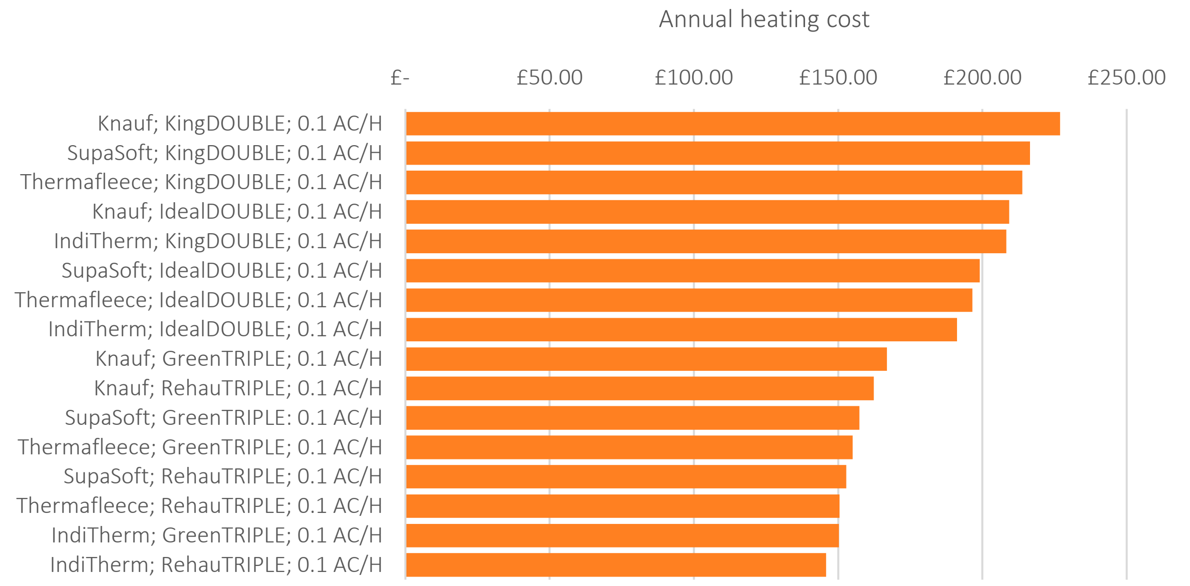


Fig. 2.5 Modelled annual heating cost for models with an infiltration rate of 0.1 AC/H

The importance of the infiltration rate is further emphasised in Figure 2.6 which illustrates the increase in annual heating cost for each version of the model compared with the results from models using the lowest target air change rate of 0.05; this value is close to the Passivhaus target of 0.03 which can be very difficult to achieve in practice.

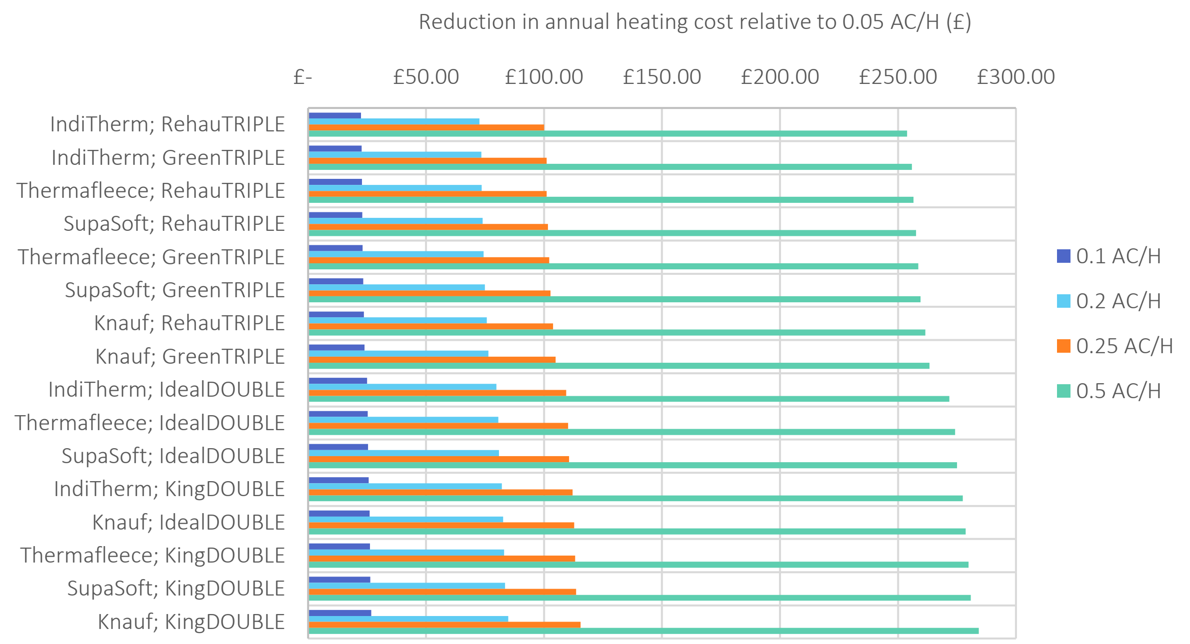


Fig. 2.6 Increase in annual heating cost relative to models using an infiltration rate of 0.05 AC/H

The final chart in this section illustrates how a selection of the modelled HTC values in the sensitivity analysis compare with various values from new build housing that have been modelled and measured in practice, many of which have been measured by Leeds Beckett University [19, 20]. As a result of the sensitivity analysis, the design team selected the SupaSoft insulation product due to its relatively low cost and modelled performance, hence the selection of HTC's presented in Figure 2.7.

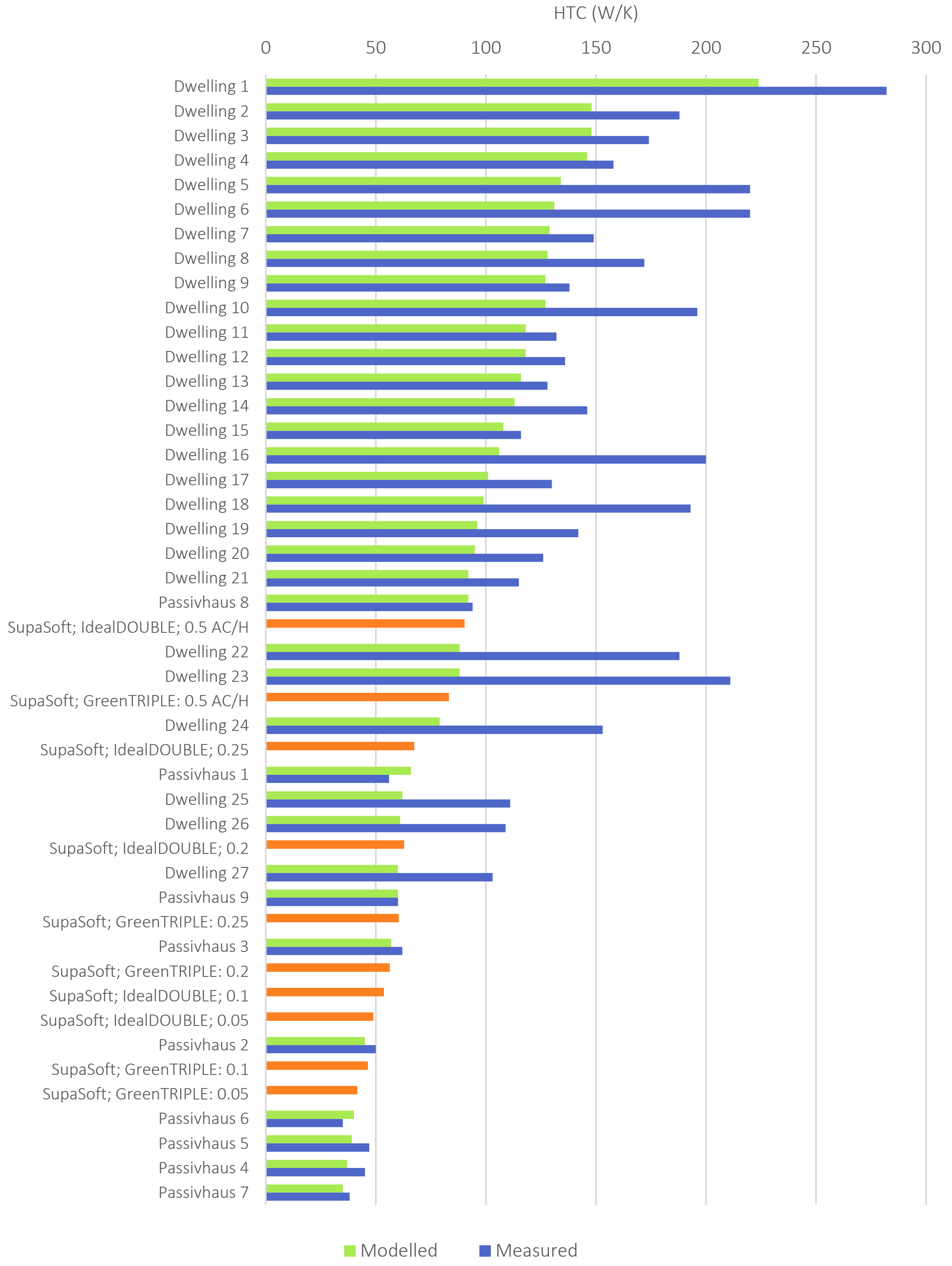


Fig. 2.7 Wikihouse modelled HTC values compared with existing dwellings

2.2 Target performance modelling

Results from the sensitivity analysis informed the selection of target design values to be used for further thermal performance modelling of both the two-bedroom house and bungalow designs. As noted above, the SupaSoft insulation material was selected based upon its cost and relative performance. The results shown in Figure 2.7 illustrate the potential gap between modelled and measured thermal performance. In this context, a target infiltration rate of 0.15 AC/H was selected as the design team felt this represented a realistic as-built value. The final fabric performance targets used in this part of the analysis are summarised in Table 2.5. All of the other model inputs for occupancy and the building systems are as described in section 2.1. It is however, important to note that, based upon the average number of occupants per m^2 of floor area, it is assumed that there are a total of 4 occupants in the house and 3 occupants in the bungalow [21]. This has an impact on internal gains and hot water consumption in particular.

Table 2.5 Target fabric performance values

Without repeat bridging			With repeat bridging			Infiltration
Walls ($W/m^2 \cdot K$)	Roof ($W/m^2 \cdot K$)	Floor ($W/m^2 \cdot K$)	Walls ($W/m^2 \cdot K$)	Roof ($W/m^2 \cdot K$)	Floor	AC/H
0.145	0.134	0.131	0.164	0.150	0.146	0.15

All model inputs for the house and bungalow versions of the Skylark design are the same expect of course for the geometry. The model geometry and floor layout for the two-bedroom house design are shown in previously Figure 2.1; model geometry and the floor layout for the two-bedroom bungalow design are illustrated in Figure 2.8.

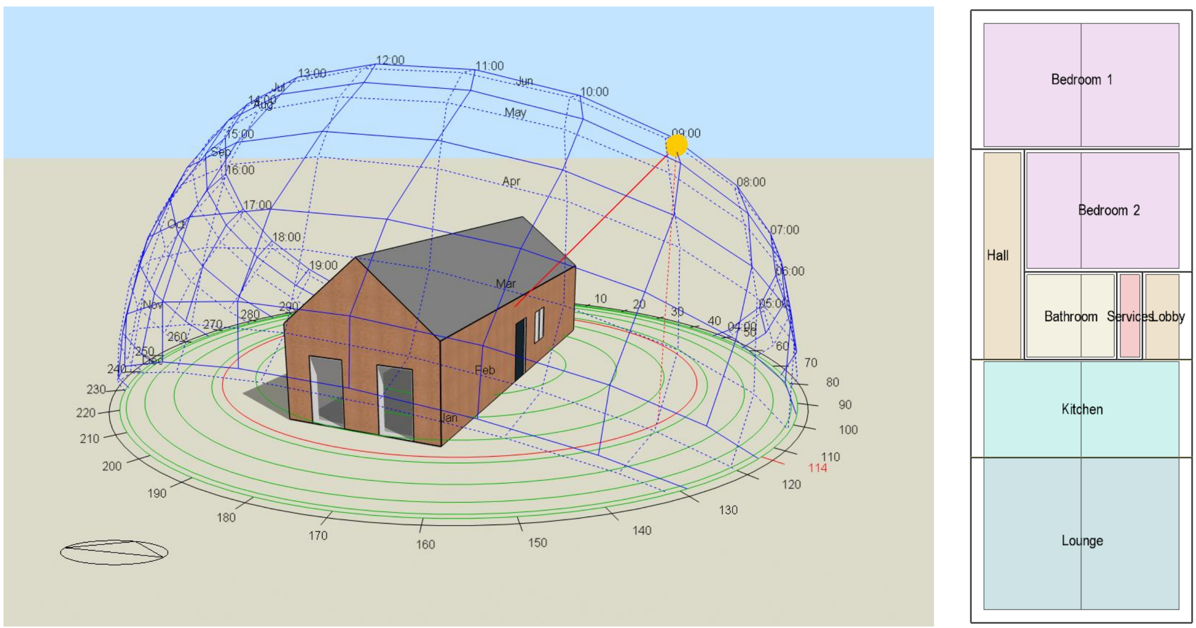


Fig. 2.8 Model geometry and floor plans for Wikihouse Skylark two-bedroom detached bungalow

2.2.1 Modelled energy use and CO_2 emissions

Using the methods and inputs described in section 2 and presented in Table 2.5, the house and bungalow were both modelled to estimate the HTC, annual energy consumption and associated utility cost and CO_2 emissions. It is the outputs from the models using the Leeds TRY weather file that are used with the LCA assessment presented in section 3. Models were also created using the minimum fabric performance that would meet UK Building Regulations L1A [11]. This helps to contextualise the estimated performance of the dwellings along with a comparison against Passivhaus targets. It is assumed in the baseline models that the buildings are simply orientated North-South as shown in Figures 2.1 and 2.8. As part of this work, the buildings were also model at 45° increments and in different UK locations. The locations are those with available CIBSE TRY weather files [5]. As these are development designs and not for a specific site at this stage, no overshading from neighbouring dwellings or local topography has been included in these models. It is important to acknowledge this as they can limit solar gains which can potentially increase overall heat demand and reduce any potential overheating.

Disaggregated modelled HTC values are shown in Figure 2.9 for the house and bungalow designs and compared with the values achieved using inputs for the fabric elements and infiltration rate that would meet the minimum standards defined in Building Regulations L1A. This again emphasises the importance of the target infiltration rate, with the maximum air permeability rate in L1A being 10 $m^3/m^2 \cdot hr$, equivalent to 0.5 AC/H. On the following page, Figure 2.10 compares the target values to a truncated selection of the modelled and measured values previously shown in Figure 2.7 [19, 20].

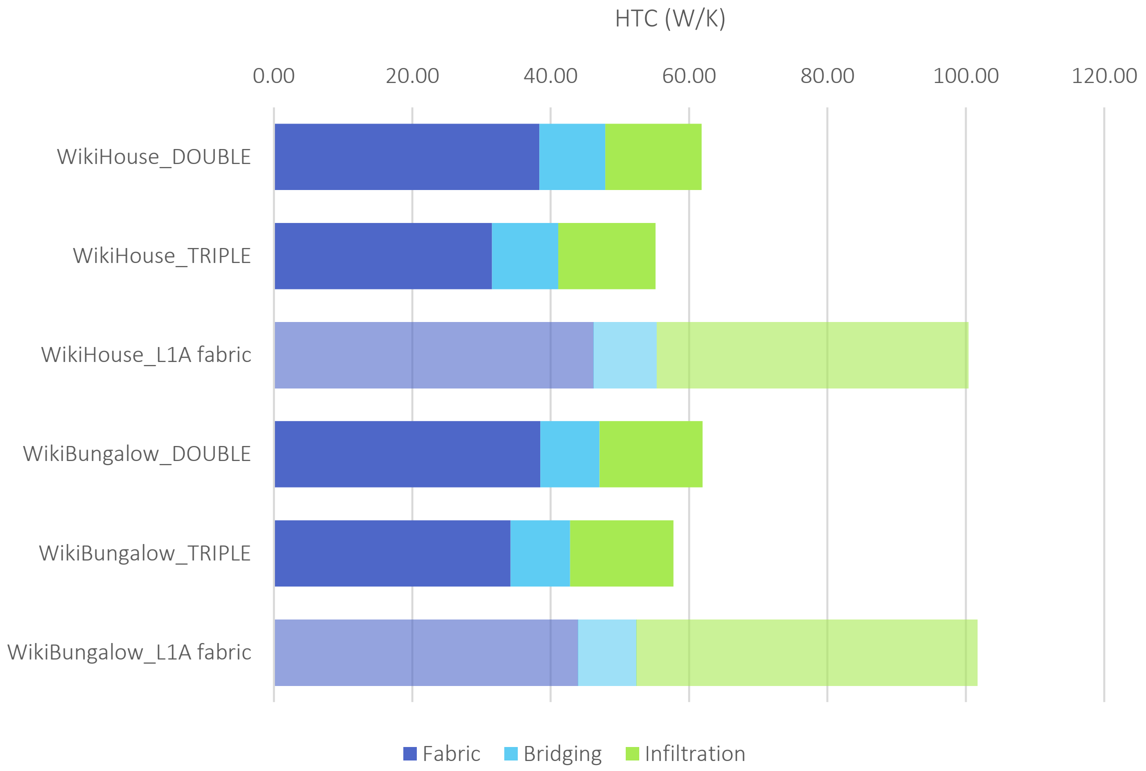


Fig. 2.9 Modelled HTC for fabric, linear bridging and infiltration in House and Bungalow designs

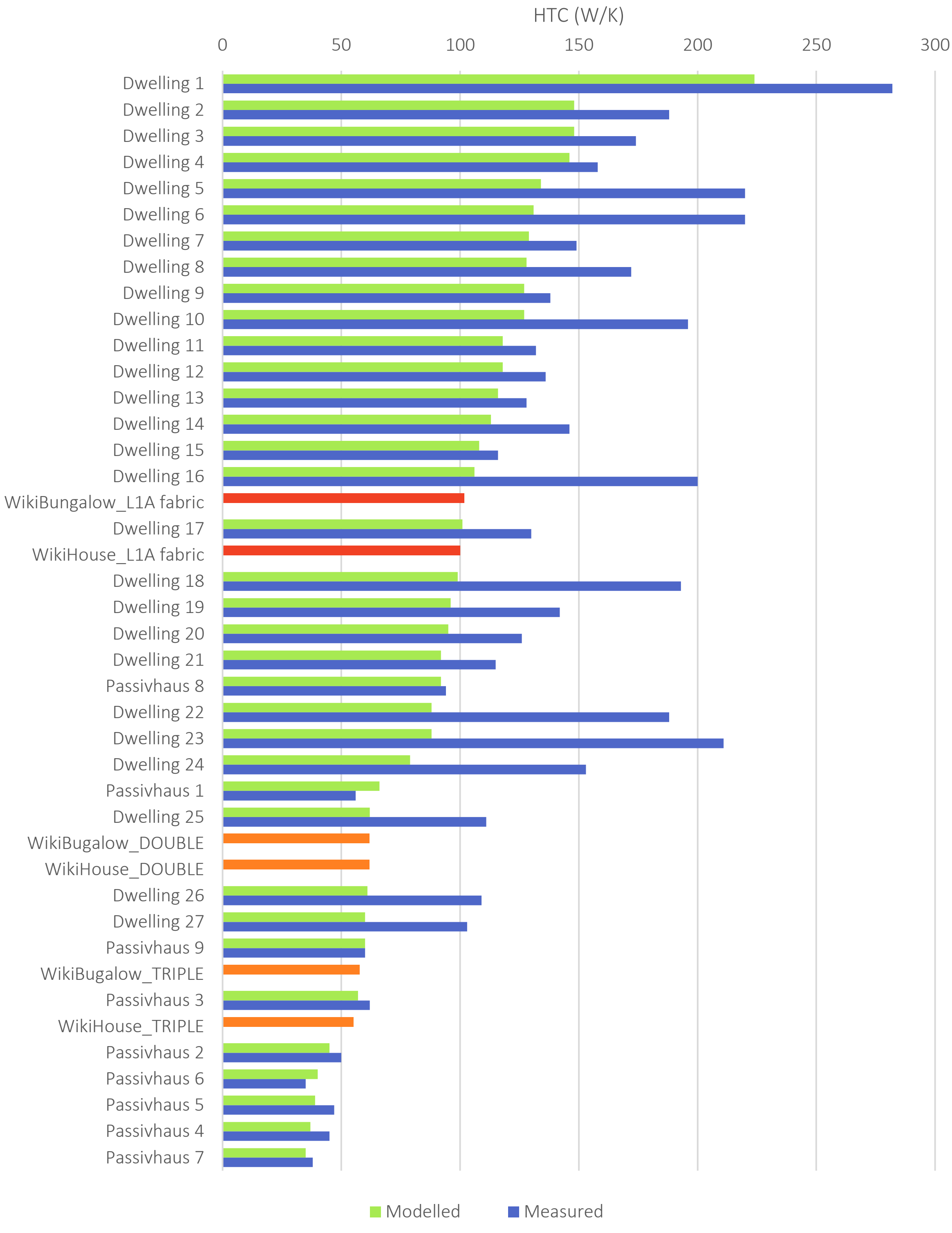
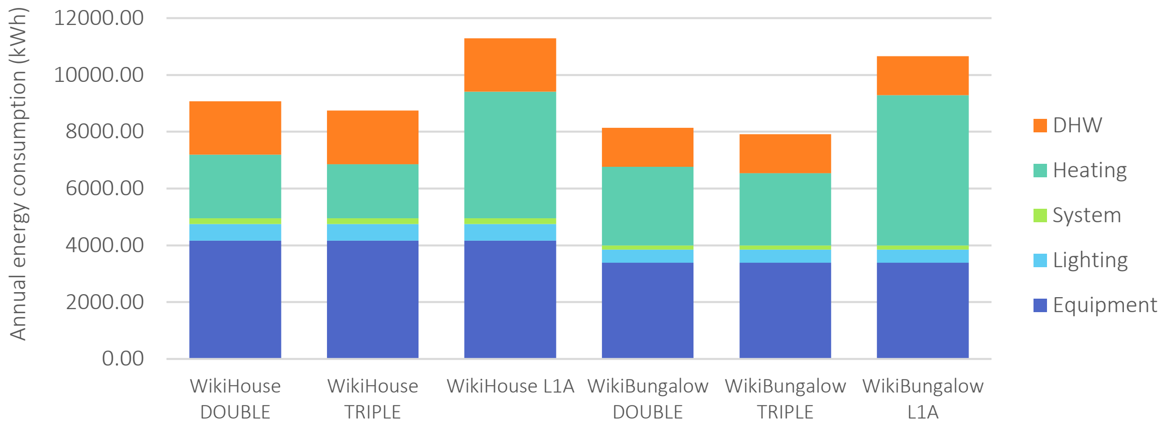
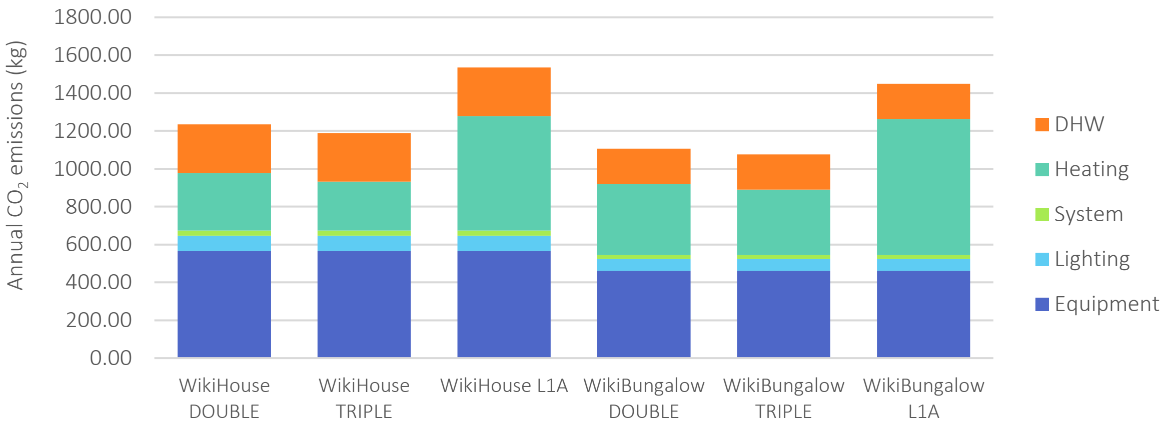


Fig. 2.10 Wikihouse target performance HTC compared with existing dwellings

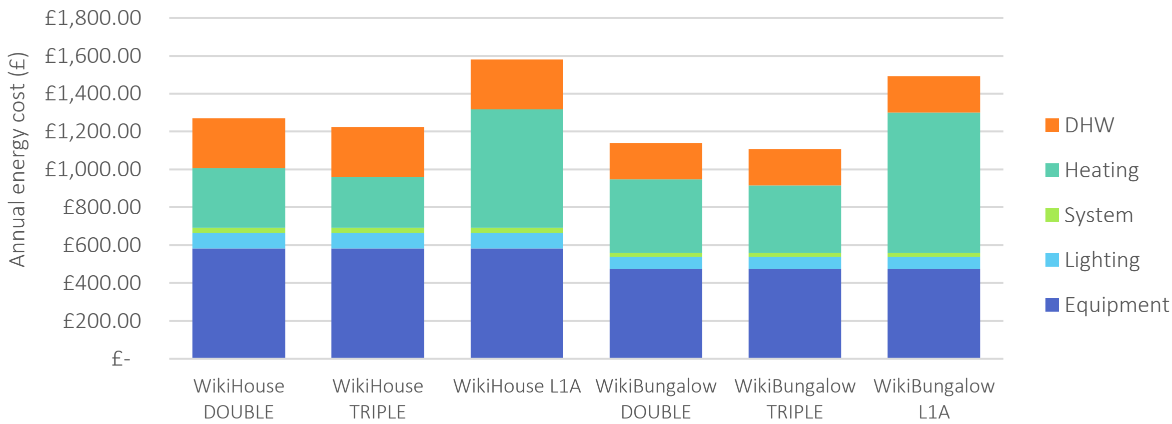
The charts shown Figure 2.11 illustrate the annual end-use energy consumption, energy cost and CO_2 emissions based upon the simple occupancy schedules described in section 2. These are again compared to results from models using the L1A minimum fabric standards. It is important to note that when comparing results with those published by other housing developers that they are likely to report the end-uses covered by regulatory compliance. Under UK regulations, SAP results do not include any consumption from equipment within the home, even though heat gains from these are included in the overall calculations.



(a) Annual energy consumption for target performance



(b) Annual CO_2 emissions for target performance



(c) Annual energy cost for target performance

Fig. 2.11 Wikihouse target performance annual simulation outputs

Renewable energy is now responsible for a growing proportion of power generation in the UK and this is forecast to increase as the government works toward a net-zero carbon target by 2035 [22, 23]. As the proportion of renewables has increased, the carbon intensity of electricity supplied through the grid has become lower. The CO_2 emissions shown in Figure 2.11 are calculated using the grid electricity carbon intensity value specific in the SAP calculation (0.136 kgCO_2/kWh). However, using the forecast decreases in carbon intensity, the annual CO_2 emissions could fall below 400 kg per year by 2035 as illustrated in Figure 2.12.

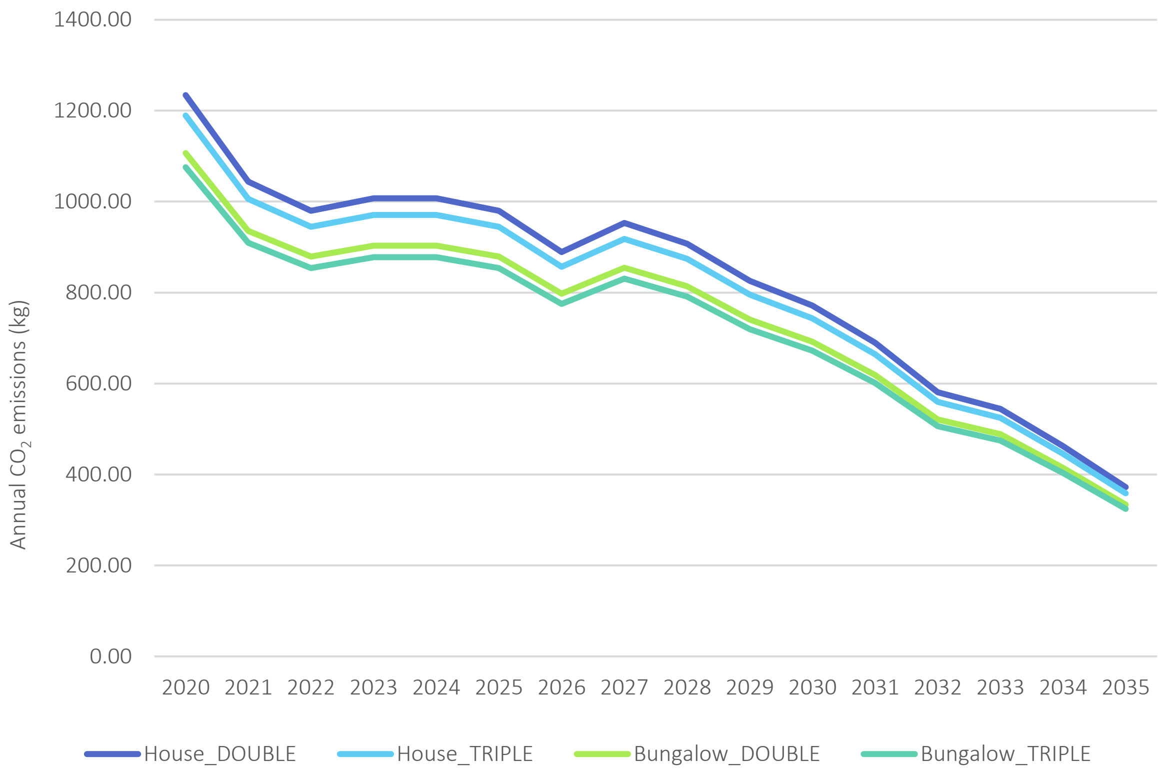
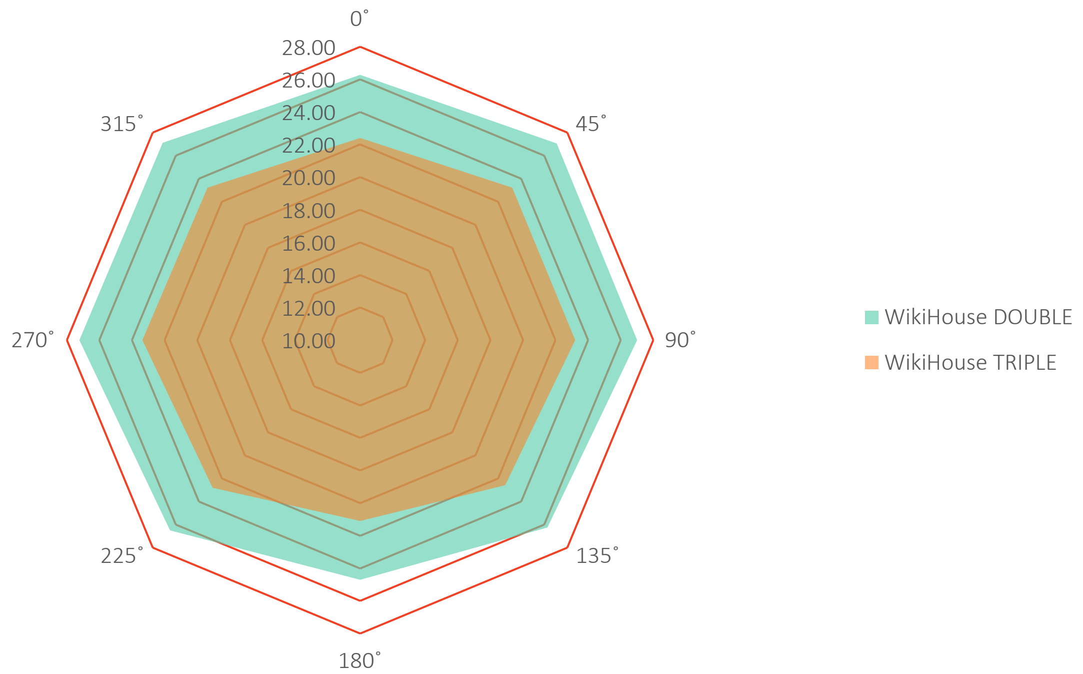


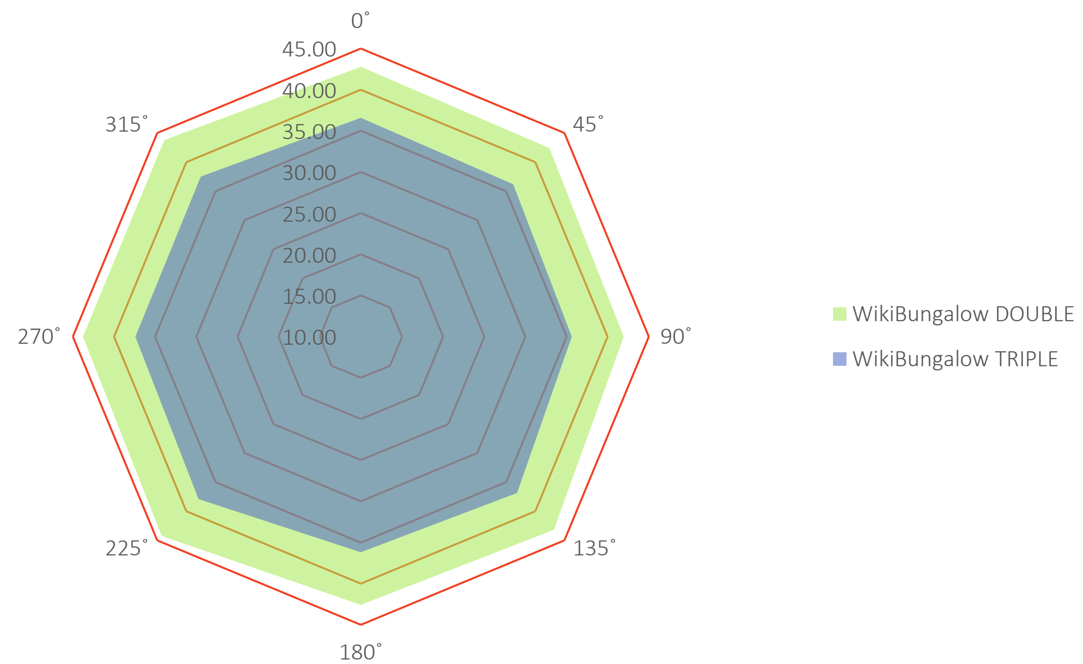
Fig. 2.12 Wikihouse annual CO_2 emissions assuming forecast carbon intensity reductions in UK grid electricity

Unitised metrics are commonly used to compare energy performance, with the kWh/m^2·year for heating metric used in Passivhaus assessment being well established. Based upon the inputs described previously, the values achieved by the Wikihouse variants are as follows: House with double glazing = 26.28 kWh/m^2·year; House with triple glazing = 22.40 kWh/m^2·year; Bungalow with double glazing = 42.78 kWh/m^2·year; Bungalow with triple glazing = 39.25 kWh/m^2·year. The values for the house compare favourably with the Passivhaus target of no more than 15 kWh/m^2·year. This is however, another instance where the validity of comparison needs to be considered. The steady-state PHPP calculation includes relatively low internal heat gains of 2.1 W/m^2 [12]. If the model inputs used here are adjusted to match these values, the triple glazed House variant would achieve a value of 32.16 kWh/m^2·year. Further to this, airtightness and HVAC inputs included in the Wikihouse models do not reflect those specified in the Passivhaus standard; if the models were altered to match these, particular the 0.03 AC/H, then the Wikihouse would achieve 18.76 kWh/m^2·year.

The kWh/m^2·year for heating demand metric has been used to illustrate the results for the models that consider the impact of alternative orientations and locations on building performance. As noted previously, the buildings are orientated North-South. The charts in Figure 2.13 illustrate the impact of orientation on the annual heating demand. As would be expected, the South facing versions of the buildings have the lowest kWh/m^2·year value but the difference between the lowest and highest values is approximately 2 kWh/m^2·year. For the double-glazed house, the difference between 180˚ (lowest demand) and 270 ˚ (highest) is 2.53 kWh/m^2·year and for the triple glazed house it is 2.27 kWh/m^2·year. For the bungalow versions the differences are 1.20 kWh/m^2·year for the double-glazed version and 1.69 kWh/m^2·year for the triple glazed building.



(a) Annual heating demand for house variants (kWh/m²)



(a) Annual heating demand for bungalow variants (kWh/m²)

Fig. 2.13 Wikihouse annual heating demand per conditioned floor area according to orientation

All four versions were also modelled for 14 different UK locations, results from this exercise are shown in Figure 2.14. For all dwellings, the highest demand occurs in Glasgow, with the double glazed house having an annual demand of 30.62 kWh/m^2·year, compared to the lowest value of 17.76 kWh/m^2·year in Plymouth; the triple glazed version of the house in Plymouth falls just below the 15 kWh/m^2·year Passivhaus threshold, at 14.85 kWh/m^2·year. The double-glazed bungalow in Glasgow has the highest demand of any variant at 49.39 kWh/m^2·year, which falls to 31.02 kWh/m^2·year in Plymouth. The bungalow design has a smaller conditioned floor area than the house (64.8 m^2 versus 85.3 m^2) but a larger volume due to the vaulted ceiling design. This, along with assumed lower occupancy and increased heat loss through roofs as opposed to walls and floors, leads to the higher unitised consumption calculated for the bungalow variants. The annual model outputs for all dwellings and locations are also listed in Table 2.6.

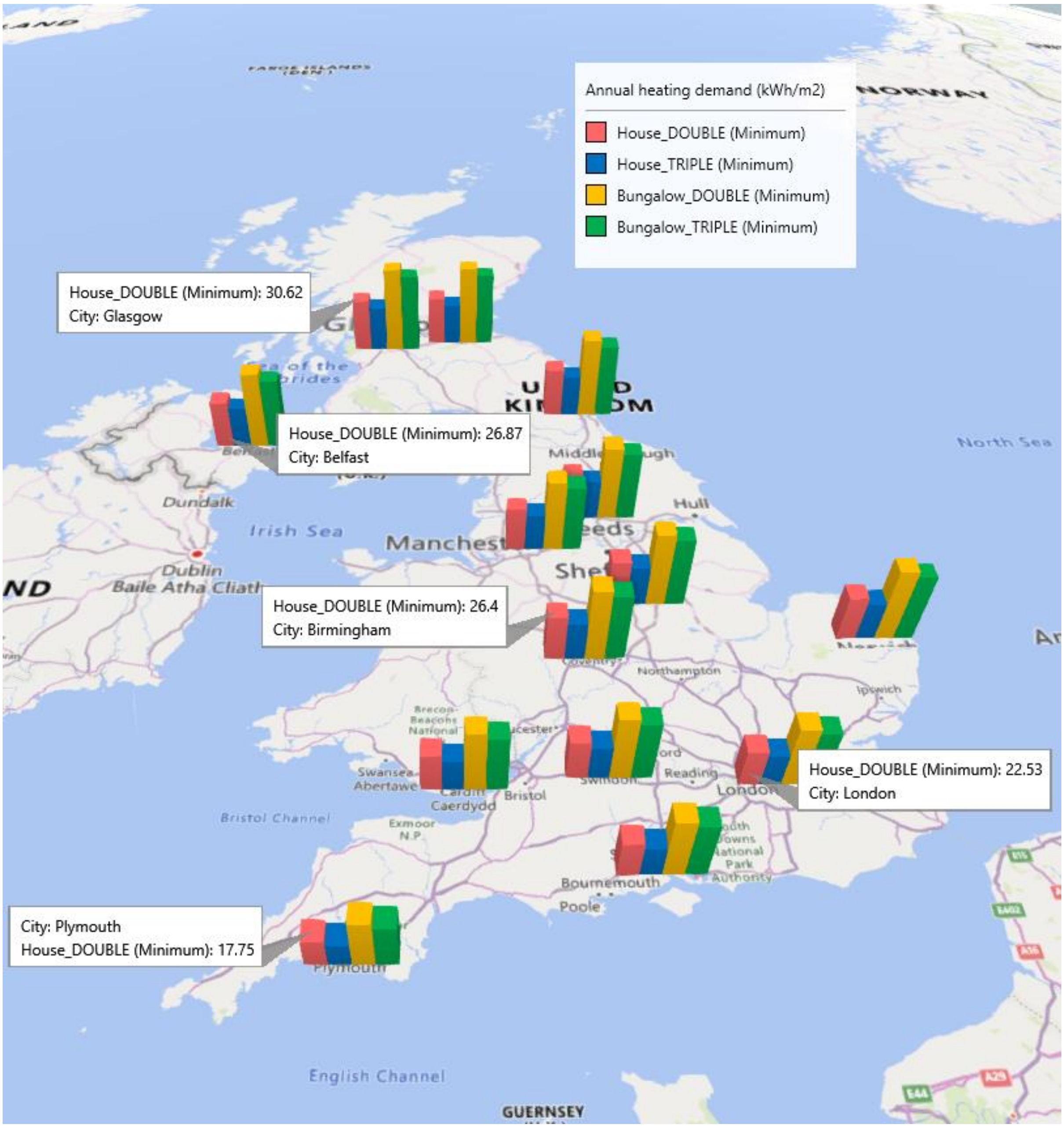


Fig. 2.14 Example Wikihouse annual heating demand in different UK locations

Table 2.6 Wikihouse annual heating demand in different UK locations

City:	House DOUBLE	House TRIPLE	Bungalow DOUBLE	Bungalow TRIPLE
Belfast	26.87	22.90	43.98	40.23
Birmingham	26.41	22.56	43.11	39.55
Cardiff	22.60	19.12	37.47	34.25
Edinburgh	28.29	24.15	46.44	42.57
Glasgow	30.62	26.17	49.39	45.32
Leeds	26.28	22.40	42.78	39.25
London	22.54	19.29	36.95	33.91
Manchester	24.78	21.04	41.16	37.66
Newcastle	28.05	23.90	45.93	42.08
Norwich	25.94	22.07	42.48	38.94
Nottingham	26.69	22.81	43.46	39.86
Plymouth	17.76	14.85	31.02	28.22
Southampton	22.43	19.05	37.45	34.28
Swindon	23.72	20.09	39.59	36.22

2.3 Overheating analysis

Due to the UK being a heating dominated maritime climate, Building Regulations have gradually increased the basic fabric performance of dwellings to reduce energy use over the year [11, 24]. In contrast to this, climate change is leading to increased summer temperatures across the globe and it has now become apparent that overheating can be an issue in the UK [25-30]. In particular, the increased airtightness of dwellings has been compounded by the changes in climate; this problem will be exacerbated in the future as the UK is forecast to begin experiencing more frequent and intense heatwave events [31-33]. This problem is further intensified in dwellings with high thermal performance. It can, however, be possible to partially mitigate the impact of these heatwave periods through design and behavioural changes.

Recently, there have been many advances in the understanding of how overheating can be modelled at design stage and also post-occupancy to provide guidance for existing tenants [26, 34-36]. Dynamic thermal simulation modelling is best suited to this type of analysis as it is not possible for steady-state monthly resolution modelling, such as SAP and PHPP, to simulate the peaks in temperature experienced during heatwave events. Using dynamic models that simulate conditions at hourly time steps allow the extreme conditions of heatwaves to be modelled reliably. It is important to note however, that the only requirement related to overheating under current Building Regulations for domestic buildings in the UK is to demonstrate that solar gains have been limited via a SAP calculation [13, 37].

Under historic guidance, overheating has simply been quantified by estimating the number of hours that exceed a simple threshold temperature but this approach has now been replaced by adaptive comfort methods that allow for the fact that people are more tolerant of higher temperatures during periods of warm weather. Inversely, people are much less tolerant of rapid changes in temperatures that lead to greater discomfort.

2.3.1 Overheating analysis using TM59

As understanding of domestic overheating has increased, the methods to model and quantify potential overheating have significantly increased in complexity. Initially a technical memorandum 'TM52 Limits of Thermal Comfort: Avoiding Overheating in European Buildings' was published by CIBSE [38] to provide guidance on how overheating can be assessed by practitioners. Subsequently, CIBSE publishing guidance to simplify the modelling of overheating in dwellings in the document "TM59: Design methodology for the assessment of overheating risk in homes" [39]. It is this methodology that has been used in this work. In simple terms, the TM59 method introduces a set of operating profiles that simulate the worst case scenario of continual occupancy under average heatwave conditions; this uses a Design Summer Year (DSY) weather file that is morphed to reflect conditions for the year 2020. There are, however, three different DSY files available for all 14 locations. They use actual year weather data that simulate different heatwave intensities: DSY1 represents a moderately warm summer; DSY2 represents a short, intense warm spell; and DSY3 a longer, less intense warm spell. These are also morphed to represent expected conditions in the 2020s, 2050s and 2080s [5].

Both Wikihouse designs were simulated following the TM59 guidance to assess the potential for overheating initially using DSY1 files for the current climate for Leeds (based upon historical data up to 2016) and for future climate scenarios for the years 2020, 2050 and 2080. The same assessments were then carried out using the DSY2 and DSY3 weather files. As the future scenario files are probabilistic, there are numerous versions of each based upon different emission scenarios (low, medium and high) and the probability of changes in climate. Although perhaps a little pessimistic, the files for the high emissions scenarios at the 50th percentile have been used in this work.

As Real Living Homes are initially looking to develop projects within the North of England, the results based upon the Leeds weather files are of immediate use. However, Leeds does not necessarily experience the same intensity of heatwaves as the South of the country. There is also no current allowance for the Urban Heat Island (UHI) effect in any of the weather files outside of London [40]. The Greater London Authority recommend that new buildings in the city are assessed using files based upon data from urban, suburban and rural sites for three different scenarios: 1976 – a prolonged period of sustained warmth; 1989 – a moderately warm summer (the current design year for London); and 2003 – a year with a very intense single warm spell. To provide a more comprehensive assessment the central London (urban) weather files have also been used to assess the potential for overheating [5, 41].

It is important to note that in the TM59 method, it is assumed that windows are opened when internal temperatures reach 22°C. Although this may not always be the case in reality, using this threshold temperature demonstrates the potential for overheating to be mitigated within the dwelling. It is important to note that not all occupants may be willing to open windows as specified in this analysis. For instance, occupants in the bungalow design may not feel safe to open windows overnight. This is however, beyond the scope of this early design stage analysis and should be dealt with for specific sites individually. Based upon advice from the design team, it has been assumed that all windows are side-hung and that 80% of the opening area can be opened during occupied periods. As natural ventilation is the main means of cooling, only the double-glazed versions of both buildings have been modelled. The MVHR system is set to include a summer bypass but this is outweighed by the natural ventilation as soon as windows are opened (the air exchanges due to the natural ventilation mean those delivered by the MVHR become insignificant).

No external or internal shading devices were included in the initial analysis and, in keeping with the heating and energy demand models, no specific external cladding was included (as agreed with Wikihouse). The initial models, therefore, consider the worst-case scenario. They are modelled as detached dwellings, the house has no openings on the East and West elevations, whereas the bungalow has a door and windows in bedroom 2 on the East elevation.

Two metrics are used to assess whether the dwelling with overheat. The first is taken from another CIBSE publication, TM52: The limits of thermal comfort: avoiding overheating in European buildings [38]. The two assessment criteria are defined as follows:

1. For living rooms, kitchens and bedrooms: the number of hours during which the difference between internal and external temperature (ΔT) is greater than or equal to one degree (K) during the period May to September inclusive shall not be more than 3 percent of occupied hours.
2. For bedrooms only: to guarantee comfort during the sleeping hours the operative temperature in the bedroom from 10 pm to 7 am shall not exceed 26 °C for more than 1% of annual hours. (Note: 1% of the annual hours between 22:00 and 07:00 for bedrooms is 32 hours).

2.3.2 Overheating results: Leeds

The DSY files for Leeds include a counter-intuitive set of conditions as the baseline DSY files actually lead to more overheating than those morphed for the 2020s. Although the morphed files for the 2020s include slightly warmer temperatures they also include some higher wind speeds and greater cloud cover which means that the results for the 2020s are lower than those for the baseline DSY files. The results for the two-bedroom house are shown in Tables 2.7 and 2.8. The zones highlighted in orange have failed the assessment, the threshold for Criteria A is 3% and for Criteria B is 32 hours.

Table 2.7 Criteria A predicted overheating for two-bedroom house

	DSY1	DSY1 2020s	DSY1 2050s	DSY1 2080s
Dining	1.75	1.10	1.70	6.04
Kitchen	0.62	0.22	0.57	2.95
Lounge	0.81	0.49	0.75	3.82
Bedroom 1	0.64	0.37	0.74	2.52
Bedroom 2	2.24	1.86	1.45	5.63
	DSY2	DSY2 2020s	DSY2 2050s	DSY2 2080s
Dining	3.24	2.85	3.97	6.41
Kitchen	1.71	1.52	2.25	3.65
Lounge	1.98	1.60	2.45	4.00
Bedroom 1	1.21	1.02	1.45	2.36
Bedroom 2	2.63	2.50	3.26	4.78
	DSY3	DSY3 2020s	DSY3 2050s	DSY3 2080s
Dining	3.40	2.79	5.17	9.11
Kitchen	1.76	1.48	2.74	5.44
Lounge	2.23	1.70	3.36	6.49
Bedroom 1	1.19	0.91	1.85	3.73
Bedroom 2	2.57	2.10	3.65	6.45

Table 2.8 Criteria B predicted overheating for two-bedroom house

	DSY1	DSY1 2020s	DSY1 2050s	DSY1 2080s
Bedroom 1	3.5	1.5	7.5	34.5
Bedroom 2	8.0	4.0	4.5	43.0
	DSY2	DSY2 2020s	DSY2 2050s	DSY2 2080s
Bedroom 1	13.0	11.0	18.5	34.0
Bedroom 2	19.0	16.5	26.0	45.5
	DSY3	DSY3 2020s	DSY3 2050s	DSY3 2080s
Bedroom 1	12.5	7.0	24.0	62.0
Bedroom 2	20.5	15.0	37.0	79.5

As can be seen from these results, the house in Leeds under DSY1 conditions would not fail this assessment until the 2080s climate scenario. This can be considered an acceptable risk given the potential life cycle of the building. Although there are instances of overheating in earlier years under the DSY2 and DSY3 conditions, additional modelling confirmed that these are easily mitigated by adding small 0.5 m overhangs to the south facing windows. This does not however, mitigate against the overheating in the 2080s and additional measures should be considered for any specific developments; a range of potential mitigation measures are discussed later in this section.

The bungalow design is naturally more susceptible to overheating due to an increased surface area to volume area and a large roof area that is coupled to all of the living space via the vaulted ceiling design. Profiles steel roofing mounted on 50 mm battens is included in the bungalow model which does create a ventilated air space between the roofing and the roof construction. However, without any shading in place, the South-facing Lounge zone in bassline model (DSY1) failed the assessment. Therefore, external shading was added for the baseline bungalow model. A 0.5 m overhang did not provide enough shade to mitigate this. The two options that led to the space passing the assessment were either a 1.0 m overhang or 0.5 m overhang and sidefins; the second option was selected for the remaining simulations.

Table 2.9 Criteria A predicted overheating for two-bedroom bungalow

	DSY1	DSY1 2020s	DSY1 2050s	DSY1 2080s
Bedroom 1	0.10	0.03	0.38	1.20
Bedroom 2	0.00	0.00	0.18	0.55
Kitchen	0.16	0.30	0.52	2.47
Lounge	0.51	0.93	0.98	4.15
	DSY2	DSY2 2020s	DSY2 2050s	DSY2 2080s
Bedroom 1	0.77	0.75	1.03	1.03
Bedroom 2	0.53	0.46	0.67	0.67
Kitchen	1.63	1.44	2.00	2.00
Lounge	2.50	2.21	2.81	2.81
	DSY3	DSY3 2020s	DSY3 2050s	DSY3 2080s
Bedroom 1	0.44	0.32	0.85	2.32
Bedroom 2	0.12	0.08	0.35	1.25
Kitchen	1.09	0.81	1.79	4.08
Lounge	1.76	1.37	2.79	5.97

Table 2.10 Criteria B predicted overheating for two-bedroom bungalow

	DSY1	DSY1 2020s	DSY1 2050s	DSY1 2080s
Bedroom1	1.5	0.5	6.0	32.0
Bedroom2	3.0	1.0	5.5	42.5
	DSY2	DSY2 2020s	DSY2 2050s	DSY2 2080s
Bedroom1	14.0	12.5	19.5	19.5
Bedroom2	22.5	19.0	28.5	28.5
	DSY3	DSY3 2020s	DSY3 2050s	DSY3 2080s
Bedroom1	10.5	6.5	22.5	66.5
Bedroom2	10.5	5.0	23.5	81.0

The introduction of 0.5 m overhangs and sidefins mitigates against overheating in the bungalow for all scenarios apart from the 2080s. Again, this could be considered an acceptable risk given the relatively modest nature of the mitigation methods introduced.

2.3.3 Overheating results: London

At least one zone of the baseline house model fails the overheating assessment for the for all of the London DSY current climate scenarios. For the most extreme scenario, the 1976 heatwave, every zone fails the assessment. Adding some exterior cladding (weather board on 50 mm battens) does make a little difference, but it not until 0.5 m overhangs and sidefins are introduced that the house passes the assessment for any of the DSY current scenarios. As noted, these represent the most extreme conditions that are likely to be encountered in the UK and it is unlikely that detached, completed unshaded dwelling would be built in central London. This analysis does, however, illustrate how the dwellings would perform in much warmer conditions.

Table 2.11 Criteria A predicted overheating for two-bedroom house

	1976	1976 (2020s)	1976 (2050s)	1976 (2080s)
Dining	3.92	6.58	8.92	12.67
Kitchen	2.73	4.02	7.18	10.38
Lounge	3.11	5.44	7.90	11.28
Bedroom 1	1.77	2.86	4.35	6.18
Bedroom 2	2.67	4.02	5.19	7.68
	1989	1989 (2020s)	1989 (2050s)	1989 (2080s)
Dining	1.21	1.77	4.55	12.33
Kitchen	0.89	1.21	2.15	8.05
Lounge	0.96	1.34	3.24	9.18
Bedroom 1	0.55	0.78	1.81	5.08
Bedroom 2	0.74	1.37	3.21	8.03
	2003	2003 (2020s)	2003 (2050s)	2003 (2080s)
Dining	2.86	3.90	6.47	12.44
Kitchen	2.07	2.63	4.64	8.62
Lounge	2.43	3.34	5.27	9.78
Bedroom 1	1.44	1.86	2.99	5.40
Bedroom 2	1.92	2.62	4.62	7.83

Table 2.12 Criteria B predicted overheating for two-bedroom house

	1976	1976 (2020s)	1976 (2050s)	1976 (2080s)
Bedroom 1	43.0	71.5	130.5	252.0
Bedroom 2	63.0	89.5	157.5	293.5
	1989	1989 (2020s)	1989 (2050s)	1989 (2080s)
Bedroom 1	21.0	41.0	83.0	224.0
Bedroom 2	24.0	54.0	102.0	258.0
	2003	2003 (2020s)	2003 (2050s)	2003 (2080s)
Bedroom 1	43.0	73.5	131.5	269.5
Bedroom 2	48.0	74.0	136.5	255.5

As would be expected, overheating in the bungalow is also fairly extensive at the central London site. Results for the bungalow are presented in Tables 2.13 and 2.14. Although it is beyond the scope of this early design stage analysis, it is useful to explore potential mitigation against these extreme conditions. To provide an illustration of how more extreme overheating could be mitigated, some additional analysis has been carried out using the 1976 (2020s) central London weather file. This is presented at the end of this section. The following sub-section first illustrates the relevance of ventilation paths when using natural ventilation as the predominant means of cooling.

Table 2.13 Criteria A predicted overheating for two-bedroom bungalow

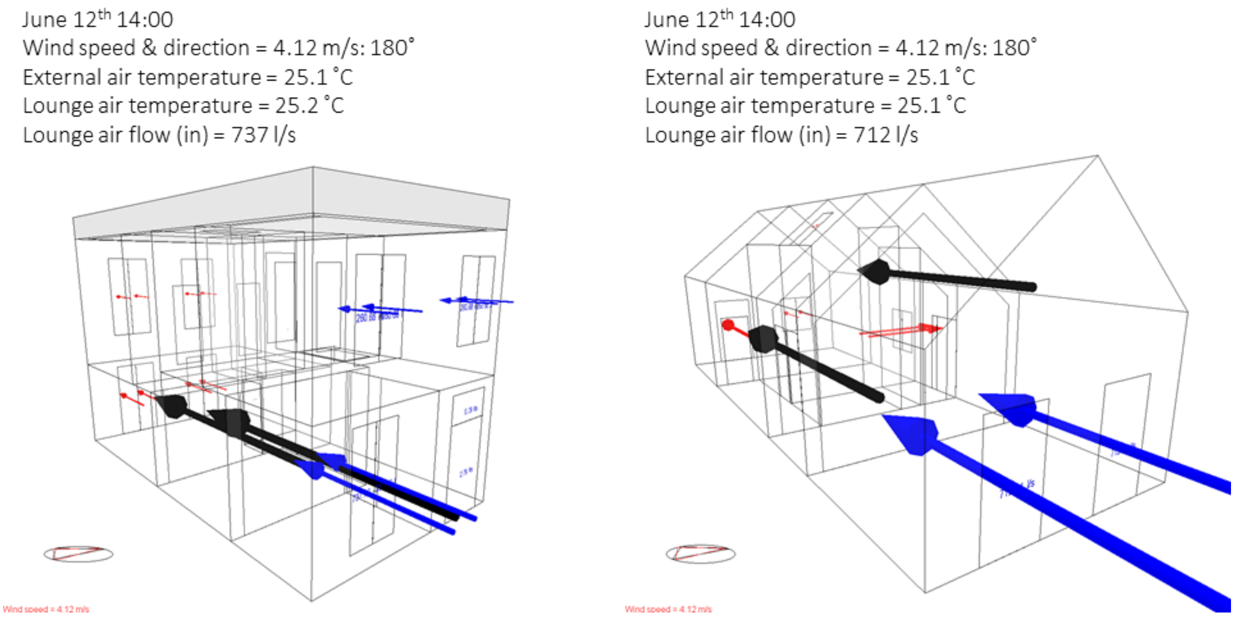
	DSY1	DSY1 2020s	DSY1 2050s	DSY1 2080s
Bedroom 1	2.00	3.25	4.63	4.63
Bedroom 2	1.27	1.92	3.31	3.31
Kitchen	3.52	5.79	8.18	8.18
Lounge	9.44	10.93	14.08	14.08
	DSY2	DSY2 2020s	DSY2 2050s	DSY2 2080s
Bedroom 1	0.59	0.99	2.30	5.81
Bedroom 2	0.58	0.74	1.25	4.39
Kitchen	1.16	2.30	5.59	12.69
Lounge	5.64	7.89	12.04	20.46
	DSY3	DSY3 2020s	DSY3 2050s	DSY3 2080s
Bedroom 1	1.62	2.33	3.34	6.12
Bedroom 2	1.14	1.49	2.46	4.73
Kitchen	3.37	4.43	7.59	12.80
Lounge	8.22	10.43	13.93	20.50

Table 2.14 Criteria B predicted overheating for two-bedroom bungalow

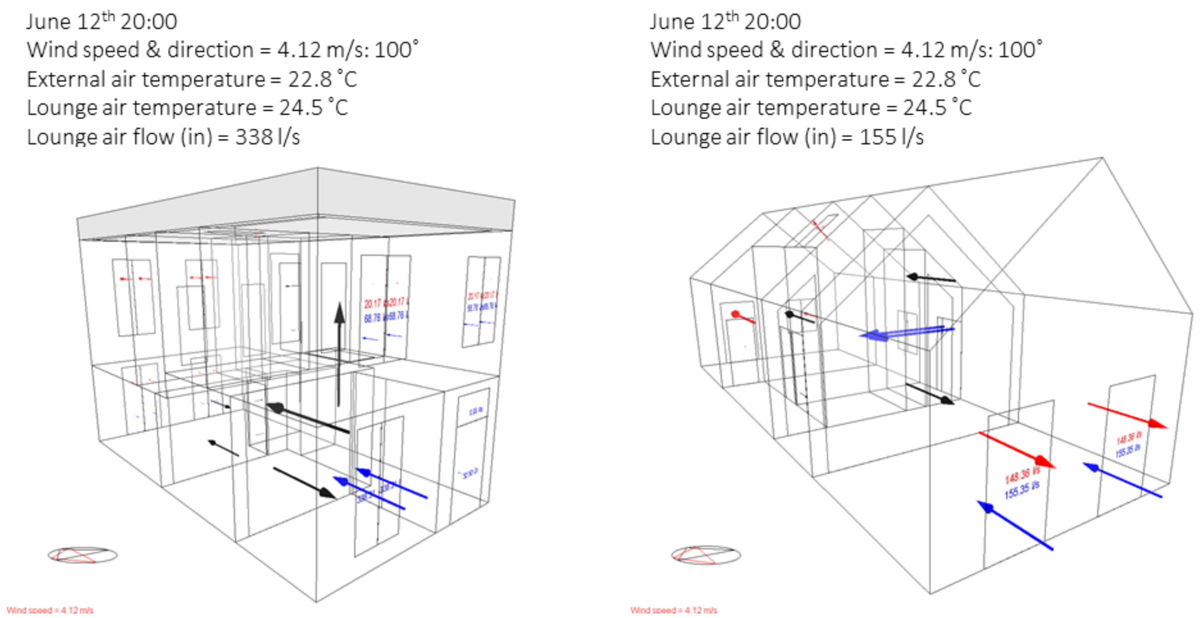
	DSY1	DSY1 2020s	DSY1 2050s	DSY1 2080s
Bedroom1	61.0	93.0	157.5	157.5
Bedroom2	51.5	80.0	159.0	159.0
	DSY2	DSY2 2020s	DSY2 2050s	DSY2 2080s
Bedroom1	26.0	46.5	98.0	258.0
Bedroom2	34.0	60.0	126.0	336.0
	DSY3	DSY3 2020s	DSY3 2050s	DSY3 2080s
Bedroom1	50.5	81.5	145.5	299.0
Bedroom2	54.5	86.5	170.5	352.5

2.3.4 Overheating: crossflow ventilation

Diagrams in this section have been produced to illustrate the importance of crossflow ventilation and also the influence on wind speed and direction in cooling the dwelling. All diagrams compare the house and bungalow designs at the same time. The house benefits from having a shallower, open plan across the ground floor which allows an unrestricted flow through this space. In contrast, the bungalow has a relatively narrow hallway connecting the living and bedroom spaces which can restrict air flow from front to back. However, the bungalow includes windows of the East façade of Bedroom 2 which provides it with and advantage when wind blows either the East or West, as opposed to the house which has no openings on either side elevation. The arrows in the diagrams are scaled to visualise the amount of air flow (litres per second), with blue arrows showing air entering the dwellings, and red arrows illustrating the air flow out of the dwellings. The black arrows illustrate the movement of air between internal zones. All temperatures are for the lounge spaces for comparative purposes.



(a) air flow at 14:00 on June 12th



(b) air flow at 20:00 on June 12th

Fig. 2.15 Crossflow ventilation for June 12th in house and bungalow designs

Figure 2.15 illustrates example air flow on a day with relatively high temperatures and a medium wind speed from different directions. The importance of the crossflow in both designs can be seen in diagram (a). In this scenario with wind blowing from the South, both dwellings can cool the internal spaces relatively well. In diagram (b), the wind is blowing from the East which helps to cool the bungalow due to the windows in bedroom 2. It can also be seen that the movement of air between the ground floor and first floor also helps to cool the house design.

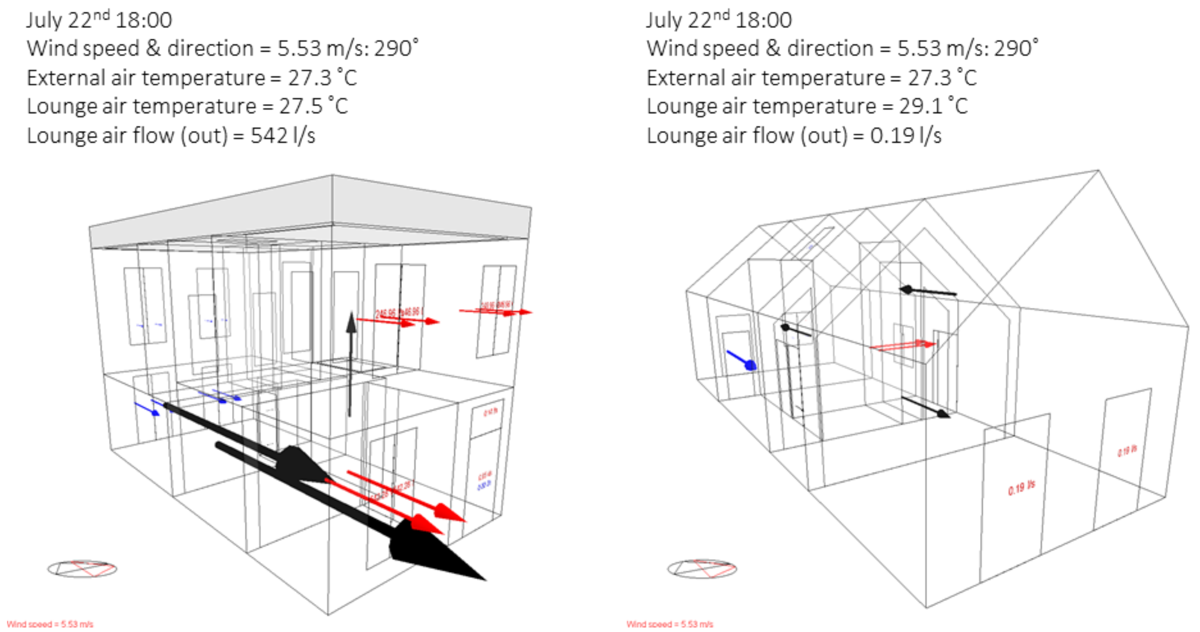
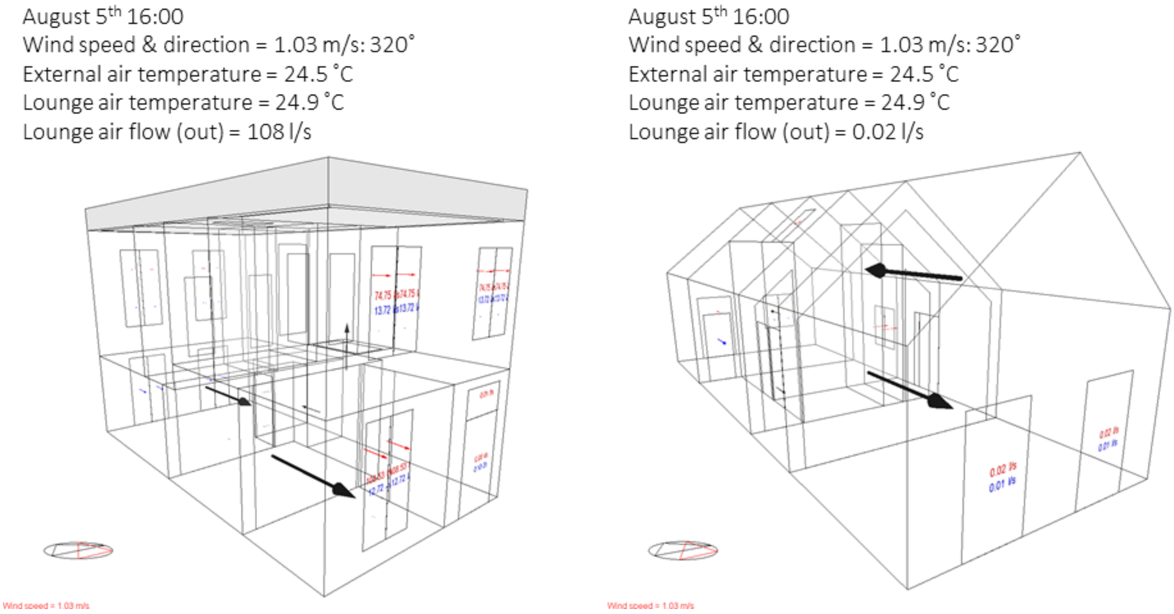
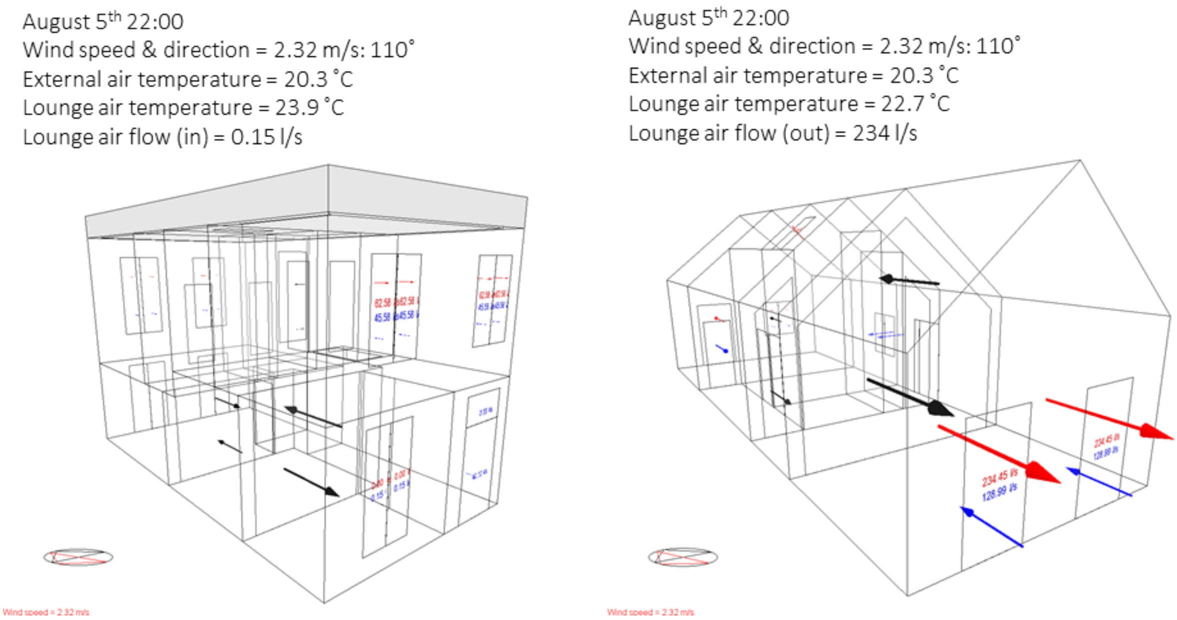


Fig. 2.16 Crossflow ventilation for July 22nd at 18:00 in house and bungalow designs

Figure 2.16 illustrates a day with high air temperature, at a time when the wind is blowing from the North-West, in this instance the benefit of the house open plan ground floor design can be seen clearly. Air flows easily through the ground floor space whereas the flow in the bungalow is restricted by the narrow hallway space. This results in the lounge space being approximately 2 ˚C cooler in the house than the bungalow.



(a) air flow at 16:00 on August 5th



(b) air flow at 22:00 on August 5th

Fig. 2.17 Crossflow ventilation for July 22nd at 18:00 in house and bungalow designs

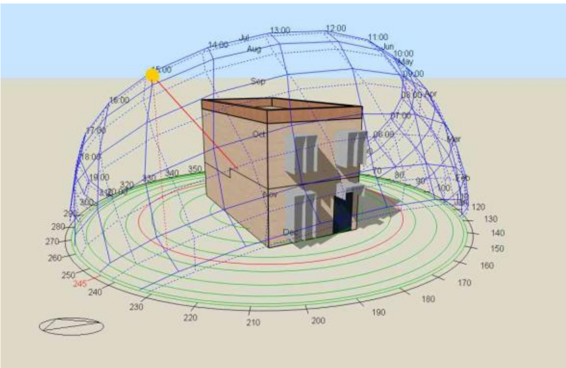
The final set of diagrams illustrate conditions on a day with moderately warm temperatures but with relatively low wind speeds. With the wind blowing from the North, both dwellings regulate temperature to the same extent. However, as the wind changes direction later in the day, the windows on the East elevation of the bungalow mean the living space temperature is approximately 1 °C. Whilst these diagrams help to emphasise the importance of crossflow ventilation paths, wind speed and direction, they also emphasise the need to consider overheating analysis on a project by project basis. Changes in orientation, plus the shading from local buildings and topography can also have a significant impact on the ability to cool spaces using natural ventilation.

2.3.5 Overheating: mitigation measures

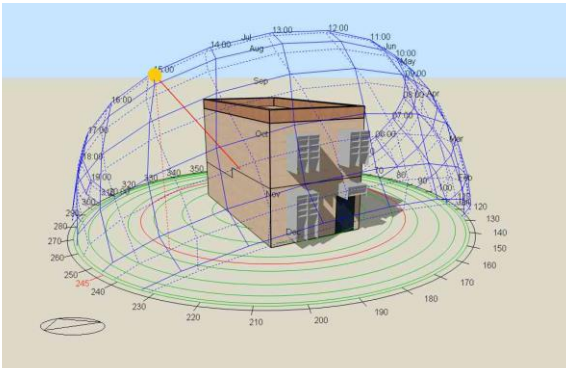
In this final sub-section, a selection of mitigating variables have been added to the house model and evaluated in the most extreme TM59 weather scenario: the Central London file from 1976 morphed for the 2020s. For the house and bungalow design to pass the TM59 assessment in central London, it was necessary to add 0.5 m overhangs and sidefins to the windows of the dwellings; these represent relatively modest mitigation measures. Also, they did not lead to either of the dwellings passing the assessment when using the 1976 (2020s) weather file. The variables modelled include:

- 'Baseline' – timber cladding with 0.5 m overhangs and sidefins
- '1 m shade' – 1 m overhangs and sidefins
- '1 m louvers' – 1 m louvers, overhangs and sidefins
- 'Internal doors' – Internal doors open all the time (bedroom doors are closed overnight in TM59)
- 'Openings East' – Additional openings on the East elevation (4 No. 0.6 x 1.75 opening windows)
- 'Openings All' – Additional openings on both elevations (8 No. 0.6 x 1.75 opening windows)
- 'Orientation' – Orientation of building East-West
- 'Local shading x1' – Shading from local buildings (same height at 9 m offset)
- 'Local shading x2' – Shading from local buildings (double height at 9 m offset)
- 'Local shading x3' – Shading from local buildings (triple height at 9 m offset)
- 'Internal PCM' – Internal thermal mass: 21 mm Phase Change Material (PCM) board
- 'Internal concrete' – Internal thermal mass: 100 mm dense concrete
- 'External concrete' – External thermal mass: 100 mm dense concrete

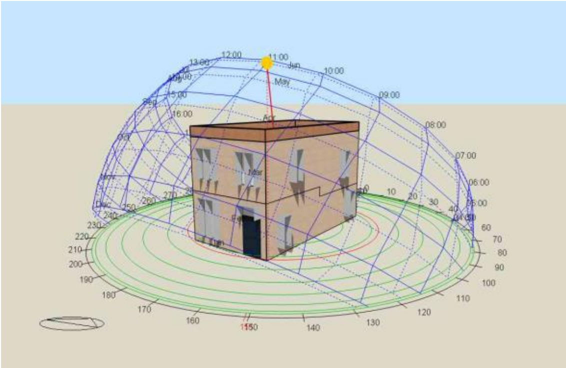
Images shown in Figure 2.18 illustrate show of the variables introduced. It is not proposed that these additions are practical in an aesthetic or material context, but they provide an indication of the extent to which additional factors could mitigate against excessive overheating in the most extreme scenarios.



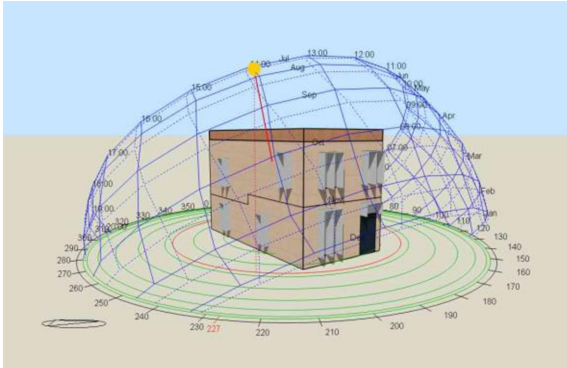
(a) 1 m shade



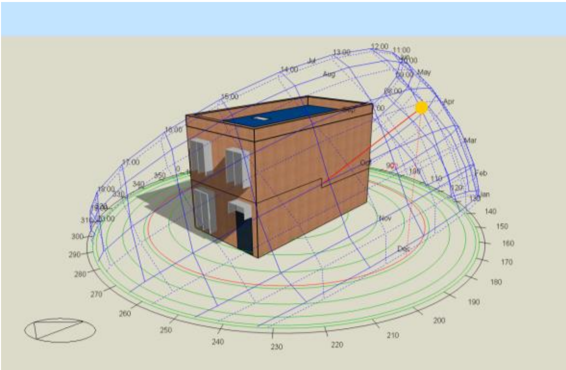
(b) 1 m louvers



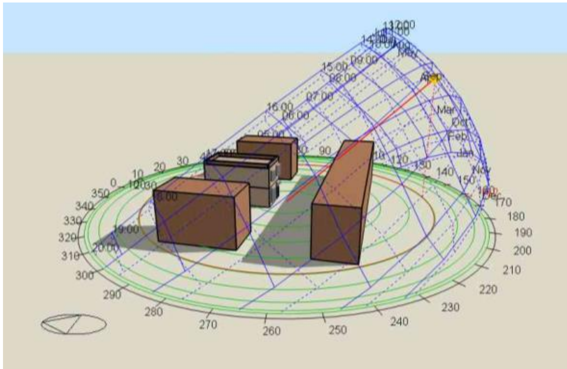
(c) Openings East



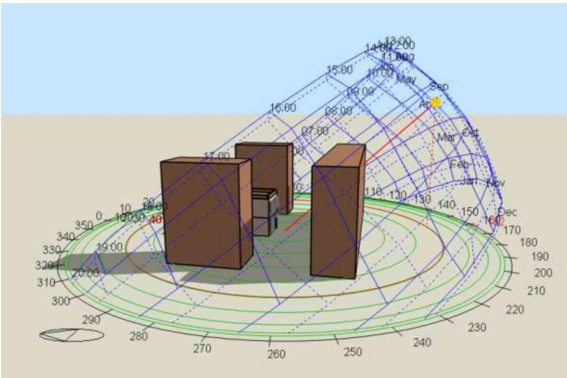
(d) Openings All



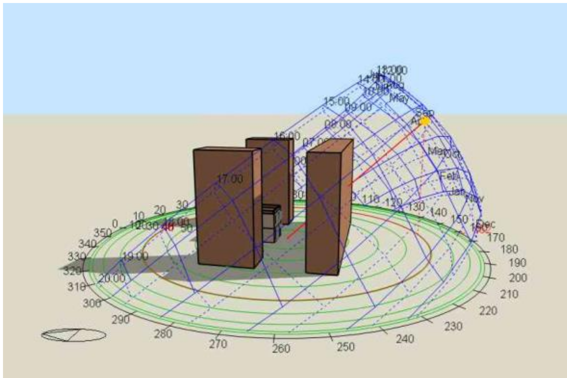
(e) Orientation



(f) Local shading x1



(g) Local shading x2



(h) Local shading x3

Figure 2.18 Physical model variables that influence overheating

There is no single variable that results in the dwelling passing the TM59 assessment under these most extreme conditions. Limiting the shortwave solar radiation that is incident on the building does have some impact, especially for the Criteria A metric. This can be seen from the results presented in Table 2.15 for models that introduce window shading; this effect is even more pronounced when local shading from taller buildings is introduced. Due to the very high air temperatures in this weather file, there are scenarios where introducing additional air flow actually increases the overheating. In these extreme conditions, it is direct shading and the introduction of thermal mass that have the greatest mitigation effect. Whilst the introduction of concrete will not be practical, the performance of the PCM would warrant further consideration for any proposed developments in this type of hot climate.

Table 2.15 Criteria A predicted overheating for two-bedroom house

	Dining	Kitchen	Lounge	Bedroom 1	Bedroom 2
Baseline	6.55	4.02	5.39	2.86	3.91
1 m shade	4.63	3.54	4.71	2.43	2.73
1 m louvers	4.00	3.34	4.50	2.22	2.43
Internal doors	6.55	4.02	5.39	2.86	3.91
Openings East	6.78	4.58	6.17	3.14	4.03
Openings All	7.59	6.78	7.64	3.92	4.70
Orientation	11.08	6.28	8.38	4.28	7.09
Local shading x1	5.54	3.74	5.21	2.75	3.48
Local shading x2	4.98	3.49	4.96	1.96	2.28
Local shading x3	3.77	3.21	4.71	1.84	1.99
Internal PCM	5.51	2.54	3.72	1.05	1.54
Internal concrete	4.18	2.91	3.54	0.99	1.33
External concrete	6.00	3.82	5.06	1.95	2.91

None of the single variable result in either bedroom passing the Criteria B assessment for overheating in the bedrooms. The results for Criteria B are shown in Table 2.16. These emphasise the limitations of the natural ventilation cooling in this scenario, although introducing additional opening does help to cool the bedrooms a little more overnight. As noted previously, this analysis is intended as indicative only and highlights the type of measures that should be considered when evaluating overheating for specific projects. Ultimately, each new development will need to be considered in isolation. As the results for Leeds show, the Wikihouse design does not lead to excessive overheating in moderate climates but may need additional design solutions when built in particularly hot climates.

Table 2.16 Criteria B predicted overheating for two-bedroom house

	Bedroom 1	Bedroom 2
Baseline	70.5	91.0
1 m shade	69.5	87.5
1 m louvers	69.0	85.5
Internal doors	70.5	91.0
Openings East	60.5	69.5
Openings All	60.0	69.0
Orientation	72.0	99.0
Local shading x1	70.5	87.5
Local shading x2	63.5	85.5
Local shading x3	60.0	83.0
Internal PCM	55.6	77.5
Internal concrete	65.0	93.5
External concrete	64.0	87.5

3.0 Life Cycle Assessment

The Life Cycle Assessment (LCA) will follow the ISO14044 [42] approach to LCA specifically following the 4 steps identified in Figure 3.1.

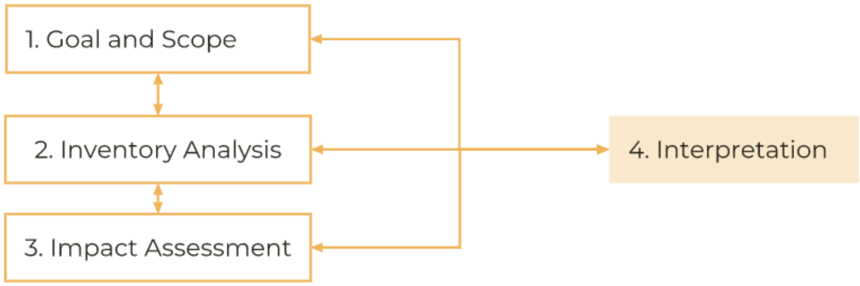


Figure 3.1 ISO14040 approach to LCA

Specifically, the LCA will follow the following structure outlined in BS EN 15878:2011 [43] for conducting LCA for Buildings outlined in Figure 3.2.

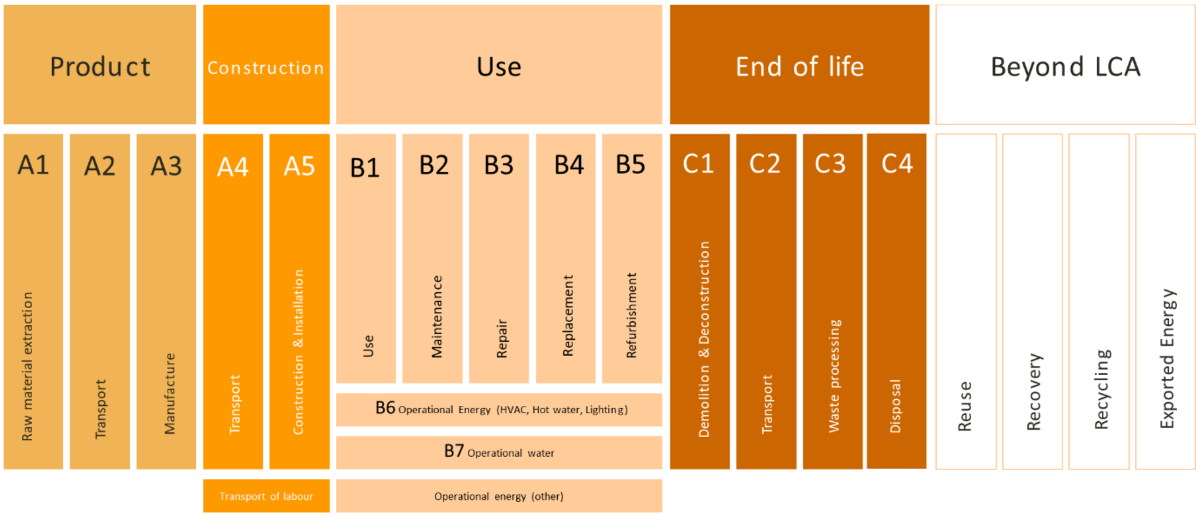


Figure 3.2 EN 15978 Building life cycle stages related to carbon emissions

3.1 Literature review

Many LCA have been undertaken to investigate the impact of houses, and specifically timber houses, some of which are listed in Table 3.1, which provides only a snap shot of current work to provide context to this assessment, in which the emissions associated with timber's emissions are of specific interest.

Table 3.1 Summary of literature on LCA of new build homes

Reference	Year	Functional Unit	Assessment period (years)	Beyond waste disposal	Biogenetic carbon
[44]	2017	m² house	50	✓	✓
[45]	2015	Whole house	100 & 500	✓	✓
[46]	2019	m² house	60	✓	✓
[47]	2018	Whole house	50	✓	x
[48]	2020	Whole house	50	✓	x
[49]	2016	Whole house	100	x	x
[50]	2019	Whole house	100	x	x
[51]	2020	m² house	50	✓	x
[52]	2021	m² house	50	✓	✓
[53]	2012	m² house	50	✓	x

Each assessment focusses on a specific research questions, and therefore, has a different functional unit or system boundary, and therefore, cannot be directly compared. However, it is possible to draw out some common features of the impacts of constructing homes and furthermore, a literature review on house LCA [54] revealed some emerging trends which add context for this LCA project.

- Natural building materials (timber, etc.) appear to have lower impacts, though only when end of life energy recovery, and biogenic carbon storage is considered.
- LCA of homes tend to range between 50 and 150 years.
- Construction based emissions appear more significant than operational emissions when the assessment period is shorter and vice versa [55].
- Transport emissions tend to be a small proportion of overall impacts [56].
- Focussing only on GHG emissions can under report the impacts of natural building materials and transport, which have more significant environmental impacts.
- Differences in system boundaries and functional units means LCA cannot be compared, for example, operational emissions are often omitted.
- Scenario analysis is limited and varies, for example, around the potential end of life treatment.
- Comparative LCA are common, though each assessment must have similar system boundaries.
- Comparisons tend to only investigate differences in emissions linked to materials and operational energy use, rather than different construction practices.

3.2 Scope and Goal

This Life Cycle Assessment (LCA) identifies the global warming potential of a Wikihouse Skylark building compared to an equivalent home built via traditional methods. The underpinning spreadsheets also facilitate scenario analyses to explore how changing specific inputs affects the overall LCA result.

3.2.1 LCA type

The project is a Cradle to Grave, Process LCA, using midpoint impacts of GHG emissions (CO_{2eq}) as its impact over 100 years.

3.2.2 LCA Functional Unit

The functional unit has been chosen to allow fair comparisons between Wikihouse Skylark buildings and traditionally constructed homes of similar standards of performance. The proposed functional unit for the LCA is:

CO_{2eq} emissions per house built to Wikihouse Skylark buildings performance standards

Comparing a Wikihouse Skylark building with houses that have lower performance would not represent a fair comparison, since these will have different construction costs and provide a different "product". Similarly there may be complications around the quality of fittings, and land costs. Additionally, data for lower-performing house types would be needed in order to undertake the assessment and while this is out of the scope of this project, it may be an area of future development.

3.2.3 LCA Scenario analysis

The initial LCA identified the hotspots in the life cycle of the Wikihouse Skylark building. This was used to inform which input parameters should be included in the scenario analysis.

3.2.4 LCA System boundary

Based on the categories outlined in Figure 3.2, the system boundary is described in Table 3.2.

Table 3.2 System boundary for LCA

	Impact Description	Scope	Justification
A1	Material extraction	✓	
A2	Transport	✓	
A3	Manufacture	✓	
A4	Transport		Same as comparison home
A5	Installation	✓	
B1	Use		Scope is carbon emissions
B2	Manufacture	✓	
B3	Repair	✓	
B4	Replacement	✓	
B5	Refurbishment	✓	
B6	Operational energy	✓	
B7	Operational water		Same as comparison home
C1	Demolition	✓	
C2	Transport		Same as comparison home
C3	Waste processing		Same as comparison home
C4	Disposal		Same as comparison home
	Beyond LCA		Same as comparison home

3.2.5 LCA Data Sources

In order that the compassions made are equitable, consistent data sources will be used. Specifically the University of Bath's Inventory of Carbon and Energy (ICE) [57] will be used where available. For the product data, where this is not used, alternative data sources such as the Environmental Product Declaration (EPD) of the building materials/products are referenced. The data linked to the Wikihouse Skylark buildings' unique processes will be provided by Wikihouse. Other data including information on the traditionally built home will be sourced from literature where necessary.

3.3 Inventory Analysis

In this section, the LCA inputs of the Wikihouse Skylark two-bedroom detached house and a cavity wall house are collated. The initial intention was to evaluate the environmental footprint of the Wikihouse Skylark building in terms of greenhouse gas (carbon dioxide equivalent) emissions throughout its life (cradle-to-grave). A comparison with a conventional building with the same dimensions and energy performance will also be undertaken and so digital twins of a detached Wikihouse and an alternative cavity wall house are developed in DesignBuilder. The U-Values of different components of the Wikihouse Skylark building under investigation (Table 3.4) are used to identify the amount of material required for the cavity wall house. It worth noting that other components (such as doors, windows, roof light, etc.) are identical in both houses, so their U-Values are not listed in Tables 3.4 and 3.6.

3.3.1 Building description

The studied Wikihouse Skylark building is a two-storey detached house with the total floor area of 92 m^2. The bill of materials along with the list of suggested suppliers received from the Wikihouse design team is available in Table 3.3.

Table 3.3 The bill of materials of the Wikihouse Skylark two-bedroom detached house

Category	Item	Material	Unit Dimensions	Suggested supplier	Quantity[1]	Unit	Remarks	Reference used to perform the LCA[2,3]
Structure	Structural Chassis	Structural spruce plywood	2440x1200x18mm	WISA Spruce Plywood	522	No(s)		[57, 58]
Structure	Internal walls and stairs	Structural spruce plywood	2440x1200x18mm	WISA Spruce Plywood	60	No(s)		[57, 58]
Structure	Underboards	WBP plywood	2440x1200x18mm		20	No(s)		[57, 59]
Structure	Screws	Carbon steel	35mm	Prodrive Recess Countersunk Screws	200	No(s)	Ignored due to negligible impact.	
Seal	Damp-proof membrane as ground cover below chassis	LDPE			56	m^2	Material is assumed.	[60-62]
Seal	Waterproof, breathable, UV membrane	HDPE & PP		Tyvek Supro	267.8	m^2		[63]
Seal	Staples for attaching breather membrane	Carbon steel		Stanley	1	No(s)	Ignored due to negligible impact.	
Seal	Insulation chassis	Recycled polyester	250mm soft fill rolled insulation (100+150mm layers)	Supasoft insulation roll	451	m^2		[64, 65]

Category	Item	Material	Unit Dimensions	Suggested supplier	Quantity[1]	Unit	Remarks	Reference used to perform the LCA[2,3]
Seal	Airtight vapour barrier	Polyethylene copolymer		Intello (by Pro Clima)	226.5	m^2		[66]
Seal	Airtight tape and seals	60mm self-adhesive heavy-duty roll		Tescon Vana (by Pro Clima)	200	m		[61]
Seal	Windows	Triple-glazed			17.98	m^2		[59]
Seal	External doors	Aluminium composite front door	Door with 800mm clear opening		2.64/0.87 (door/window)	m^2		[57, 67, 68]
Seal	Roof lights	Fixed double-glazed			2.4	m^2		[57, 67]
Skin	Rainscreen cladding	Larch cladding boards		Scotlarch Sioo treated	294.48	m^2		[57, 69-71]
Skin	Cladding battens	Treated softwood	25mm x 50mm		1094.4	m		[57, 71-73]
Skin	Cladding fixings	Stainless steel screws	50mm		Unknown	No(s)	Ignored due to negligible impact.	
Skin	Roofing material	Profile steel panels			46.1	m^2		[57, 74]
Skin	Roofing insulation	XPS tapered insulation boards			46.1	m^2		[75, 76]
Skin	Window reveals	Aluminium	L profile 140mm x 75mm		50	m		[57]
Skin	Gutters and downpipes	Aluminium square profile			20	m		[57]
Skin	Flashings and accessories	Aluminium			70	m		[57]
Skin	Plasterboard		10 mm		238	m^2	Internal walls, ceiling	[77]

[1]These values are received from the Wikihouse design team and are assumed to include necessary construction contingencies.

[2]The following references are used to calculate C1 to C4 modules in Table 3.11 for all listed items: [78-81]

[3]The following reference is used to calculate transportation emissions (A4 & C2 modules in Table 3.11): [82]

Table 3.4 The U-Values of the Wikihouse Skylark two-bedroom detached house

Component	Layer	Thickness (mm)	U-Value (W/m2K)
External wall			0.145
	Plywood (Heavyweight)	18	

Component	Layer	Thickness (mm)	U-Value (W/m2K)
	Supasoft Roll	250	
	Plywood (Heavyweight)	18	
	Air gap	32	
	Gypsum Plasterboard	10	
Flat roof			0.150
	Ethylene propylene diene monomer (EPDM)	2	
	Plywood (Heavyweight)	18	
	Supasoft Roll	250	
	Plywood (Heavyweight)	18	
	Air gap	70	
	Plasterboard	10	
Floor			0.146
	Timber Flooring	10	
	Cellular Rubber Underlay	5	
	Plywood (Heavyweight)	18	
	Supasoft Roll	250	
	Plywood (Heavyweight)	18	
	Air gap	70	
	NCM membrane	1	

3.3.1.1 The alternative cavity wall house

The studied cavity wall house is a two-storey detached house with similar shape, glazing area, floor area U-Values, and energy performance but with different construction materials (Table 3.5). The cavity wall house studied in this section is one of the typical construction types in the UK [83]. For the materials listed in Table 3.5, a 2 to 3 percent construction contingency is included [84, 85].

Table 3.5 The bill of materials of the alternative cavity wall house

Category	Item	Material	Unit Dimensions	Quantity[1]	Unit	Remarks	Reference used to perform the LCA[2,3]
External wall	Brickwork Outer	Clay	215 mm (L) x 65 mm (W) x 105 mm (T)	10234	No(s)	Contingency: 3%	[86]
External wall	Insulation	MW Stone Wool (standard board)	250mm	160	m^2		[85, 87]
External wall	Mortar	Cement: ~ 2 - 85% Filler materials: ~ 10 - 90%		13634	kg	Contingency: 2%	[84, 85, 88, 89]

Category	Item	Material	Unit Dimensions	Quantity[1]	Unit	Remarks	Reference used to perform the LCA[2,3]
		Plaster: ~ 0 - 45% Additives: ~ 0 - 6% Dispersion powder: ~ 0 - 5%					
External wall	Concrete Block (Heavyweight)	Concrete	440 mm (L) x 215 mm (W) x 100 mm (T)	1537	No(s)	Contingency: 3%	[57, 85, 86, 90]
External wall	Plaster	Gypsum	13 mm	151	m^2	Contingency: 2%	[57, 88, 90, 91]
Roof	Waterproofing membrane	PVC		43.3	m^2	Contingency: 2%	[92, 93]
Roof, Ground floor	Rigid insulation	EPS (Expanded Polystyrene)	250 mm	101	m^2	Contingency: 2%	[94]
Roof	Vapour control layer	Polyethylene foam		43.3	m^2	Contingency: 2%	[95, 96]
Roof, First floor	Structural deck	Plywood (Heavyweight)	13 mm	87	m^2	Contingency: 2%	[57, 58]
Roof, First floor	Joists	Timber	72 mm (W) x 220 mm (D) x 5.44 m (L)	52	No(s)	Contingency: 2%	[57, 71, 97]
Ground floor	Infill Layer	Gravel	200 mm	57.2	m^2	Contingency: 2%	[98]
Ground floor	Damp-proof membrane as ground cover below chassis	LDPE		57.2	m^2	Material is assumed; Contingency: 2%	[60-62, 99]
Ground floor	Concrete	1:2.5:5 cement: sand: aggregate with Ordinary Portland Cement (OPC) - CEM I		57.2	m^2	Contingency: 2%	[100]
Ground floor	Screed	Mortar or screed (1:3 cement: sand mix) (Using CEM I cement)		57.2	m^2	Contingency: 2%	[57, 100]
Seal	Windows	Triple-glazed		17.98	m^2		[59]
Seal	External doors	Aluminium composite front door	Door with 800mm clear opening	2.64/0.87 (door/window)	m^2		[57, 67, 68]
Seal	Roof lights	Fixed double-glazed		2.4	m^2		[57, 67]
Skin	Window reveals	Aluminium	L profile 140mm x 75mm	50	m		[57]

Category	Item	Material	Unit Dimensions	Quantity[1]	Unit	Remarks	Reference used to perform the LCA[2,3]
Skin	Gutters and downpipes	Aluminium square profile		20	m		[57]
Skin	Flashings and accessories	Aluminium		70	m		[57]
Skin	Plasterboard		12.5 mm	87	m^2		[77]

[1]These values include the necessary construction contingencies.

[2]The following references are used to calculate C1 to C4 modules in Table 3.12 for all listed items: [78-81]

[3]The following reference is used to calculate transportation emissions (A4 & C2 modules in Table 3.12): [82]

Table 3.6 The U-Values of the alternative cavity wall house

Component	Layer	Thickness (mm)	U-Value (W/m^2K)
External wall			0.145
	Brickwork Outer	105	
	MW Stone Wool (standard board)	250	
	Concrete Block (Heavyweight)	100	
	Plaster (Lightweight)	13	
Flat roof			0.150
	Bitumen, felt/sheet	6	
	Expanded Polystyrene	250	
	DuPont Tyvek 1060B (HDPE)	0.2	
	Plywood (Heavyweight)	13	
	Air gap	70	
	Plasterboard	12.5	
Floor			0.146
	Gravel	200	
	Monarflex 1200-gauge DPM (LDPE)	0.3	
	Expanded Polystyrene	250	
	Cast Concrete	100	
	Cement/plaster/mortar - cement screed	50	
	Synthetic Carpet	10	

3.3.2 Declared unit (DU)

Depending on the data source, material, and the conductor of an LCA study, different units of a product (known as the declared unit) could be used to report its environmental impacts like CO_2 emissions. Such a unit could be in the following forms for reporting CO_2 equivalent emissions per declared unit of the product: kg CO_2 eq / m^3; kg CO_2 eq / kg; kg CO_2 eq / tonne; kg CO_2 eq / window, etc. However, the cumulative CO_2 emissions would be reported in terms of kg CO_2 eq or tonne CO_2 eq for the entire system throughout its life (here, the Wikihouse Skylark building and the alternative house, see Section 3.4).

3.3.3 System boundaries

This study covers cradle-to-gate (A1 – A3), construction process stage (A4 – A5), use stage (B6), and end-of-life stage (C1 – C4). These stages are discussed briefly in Sections 3.3.7.

3.3.4 Cut-off rules

As discussed earlier, this LCA considers individual EPDs (if available) and the ICE dataset as its data sources. In the case of the former, most of the EPDs comply with the 1% cut-off criteria of BS EN 15804 for the exclusions/missing data [101]. In the case of the latter, the 80:20 Pareto Principle advised by [61] is considered.

3.3.5 Reference service life (RSL)

It should be noted that while the expected service life of the two houses in this LCA is 100 years, some of the individual components have a lower service life. The impact of the replacement of these components is also considered in this LCA.

3.3.6 LCA-software

No specific software was used to perform the LCA in this study. However, most of the EPDs referred to the database of GaBi or thinkstep AG [102] to take the background data for their LCA models.

3.3.7 Life cycle stages

The life cycle stages considered in this LCA are identified with (X) in Table 3.7. Those modules not considered in this LCA are identified with ND = Not Declared.

Table 3.7 Description of the system boundary (X = Included; ND = Not Declared)

Product stage			Construction process stage		Use stage							End-of-life				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	X	X	ND	ND	ND	ND	ND	X	ND	X	X	X	X	ND
Raw material supply	Transports	Manufacturing	Transports	Installation	Use	Maintenance	Repair	Replacement	Refurbishment	Energy use	Water use	Demolition/De-construction	Transports	Waste processing	Disposal	Reuse, Recovery, Recycling

3.3.7.1 Product stage; A1-A3

According to individual EPDs and the ICE dataset [57], the product stage includes:

- Sourcing
- Pre-products manufacturing
- Packaging
- Transport to the factory
- Production
- Fuels and energy used
- Production stage waste processing
- Energy supply

However, most of the sources referred to in this study do not report A1, A2, and A3 individually. Therefore, this study reports the results of this stage cumulatively under the product stage and not individually for A1 to A3 modules (Section 3.4). It should be noted that, following the official EPD of building components/materials [58], this study reports A1-A3 values of timber products considering the captured carbon by wood during its lifetime.

3.3.7.2 Construction process stage; A4-A5

A4; Transport

Individual products and materials are either transported to the construction site or a machining shop. If the machining shop is not located on-site (which applies to the Wikihouse Skylark building), second transportation from the shop to the site is included. In this study, the primary source of data for A4 is the EPD of a product. Wherever the EPD was unavailable, or second transportation was envisaged, the following assumptions were made while calculating the transport emissions during the construction stage

(Table 3.8). The impact of transport on the overall LCA was marginal and s further sensitivity analysis on the distance travelled by materials was not undertaken.

Table 3.8 Assumptions to calculate emissions from delivery vehicles [80, 82]

Parameter	Unit
Vehicle type	HGV (diesel), Articulated (44 GWt)
Load capacity	65% laden
Distance	320 km
Emission	0.92 kg CO_2 equivalent/km

A5; Construction/installation process

The primary source of data to calculate the global warming impact of the buildings in this module is the EPD of the products. In this section, no additional wastage is considered for the Wikihouse Skylark building as it was assumed included in the bill of materials (Table 3.3). However, an additional 2 to 3% wastage of materials is considered for the alternative cavity wall house [84, 85].

According to the developers of the Wikihouse Skylark building, 5980 kWh per house is consumed to machine the plywood sheets to the desired shapes at shop. An emission conversion factor of 0.21233 kg CO_2/kWh is considered to calculate A5 for the Wikihouse Skylark building [80]. However, no shop fabrication is considered for the cavity wall house.

The construction of a cavity wall house could take up to one year, which excludes the time required for research and pre-planning that could take another one year [56, 103]. During the construction phase, a considerable amount of energy would be consumed for lighting, machinery, etc. The total energy used during the construction of the cavity wall house is sourced from the literature and is estimated to be 21.6 GJ, resulting in 36 tonne CO_{2eq} (2012 data) [56]. On the other hand, the construction of a modular house such as the Wikihouse Skylark building is expected to take half of the time necessary to build a cavity wall house and requires considerably lower capacity machinery. However, since the details necessary to calculate the construction stage emissions were not available for the Wikihouse Skylark building (i.e., duration of construction, type of machinery required, etc.), the potential CO_2 emissions related to these activities were excluded for both buildings.

3.3.7.3 Use stage; B1-B7

B6: Operational energy use

The operational energy use emissions reported in Section 3.4 considers the current and forecast carbon intensity of electricity supplied through the grid (Section 2.2.1). The reported value in Tables 3.11 and 3.12 is the sum of CO_2 emissions based on the modelled energy use from 2020 to 2035 (Figure 2.12). While the service life of the two houses is 100 years, it is expected that after 2035, the share of the operational phase in the overall carbon footprint of these buildings is negligible. Therefore, the operational phase CO_2 emissions from 2036 onward are not included in B6.

3.3.7.4 End-of-life stage; C1-C4

C1; De-construction/demolition

The Wikihouse Skylark building is assumed to be fully de-constructable. Since most of the deconstruction work is performed manually, no emissions are considered for the Wikihouse Skylark building for the C1 module (the impact of small machinery for soft stripping is ignored). On the other hand, the brick-and-block building is assumed to be demolished at its end of life. This is because cement-based mortars currently used in the construction of these houses make successful deconstruction less likely [104, 105]. For the demolition of the cavity wall house, it is assumed that an excavator would complete the task in eight hours. Below is the details of the excavator (Table 3.9) and the formulae used to calculate C1 for the cavity wall house [106].

GHG emissions (gal) = 10.15*(soil quantity/productivity rate) * fuel consumption rate * engine horsepower — Equation 2.1

GHG = 10.15 * [Q/(-0.521HP+141.5B-10.23C+290.73E+S)] * HP * 0.04 gal/hp.hr — Equation 2.2

In Eq. 3.1, soil quantity / productivity rate (Q/(-0.521HP+141.5B-10.23C+290.73E+S) in Eq. 3.2) gives the total time in hours required to perform the demolition task and cleaning the site using the excavator. In the above formulas, 10.15 is the amount of CO_{2eq} emissions per gallon of diesel fuel [106].

Table 3.9 CAT excavator specification [106]

Excavator model	Capacity of Bucket (lcy)	Size of Engine (hp)
CAT-315C	1.13	115

C2; Transports

Based on [81], transport distance (including initial waste collection) to waste processing is assumed to be 125 km to a recycling facility, 35 km to an incinerator/energy recovery unit, and 35 km to a landfill. The same vehicle type used in module A4 is considered in module C2 (Table 3.8).

C3 – C4; Waste processing and disposal

The UK statistics on waste [78] is used to identify the amount of each category of waste (i.e. recycled, incinerated, and landfilled) (Table 3.10). It should be noted that for "Recovery other than energy recovery – Backfilling", no transportation emission is considered as in-situ usage of waste under this category is assumed.

Table 3.10 Share of different waste treatments practised in the UK [78].

Waste description	Energy recovery	Incineration	Recovery other than energy recovery – Except backfilling	Recovery other than energy recovery – Backfilling	Deposit onto or into land
Metallic wastes, ferrous	0.00%	0.00%	97.89%	0.46%	1.65%
Metallic wastes, non-ferrous	0.00%	0.00%	99.99%	0.00%	0.01%
Glass wastes	0.00%	0.00%	95.19%	0.03%	4.78%
Plastic wastes	0.00%	0.38%	90.90%	0.00%	8.71%
Wood wastes	15.39%	18.83%	61.61%	3.46%	0.71%
Discarded equipment	0.00%	0.00%	99.26%	0.00%	0.74%
Mineral waste from construction & demolition	0.00%	0.00%	94.78%	1.12%	4.10%
This table is developed based on Table 5.4 of [78], "Total waste sent to final treatment, split by method of treatment and EWC-STAT waste material, 2010-16, UK"					

To calculate C3, it is the gross emissions (i.e., the total emissions during waste processing) and not the net emissions (i.e., the material savings as the result of recycling) that is considered. The emission factors for different stages of waste processing and disposal is sourced from [79, 80].

3.4 Impact Assessment

Using the bill of materials in Tables 3.3 and 3.5, and considering all assumptions made in Section 3.3, along with the modelled operation emissions, the global warming impact of the studied houses are calculated and presented in Tables 3.11 and Figure 3.3.

Table 3.11 The LCA of the Wikihouse Skylark and alternative cavity wall building (kgCO$_2$.eq / 100 years)

Impact category	A1 – A3	A4	A5	B6	C1	C2	C3	C4	Total
Wikihouse Skylark	-23,419	1,863	4,267	12,768	0	199	25,764	194	21,636
Wikihouse Skylark to meet Part L1A	-23,419	1,863	4,267	15,354	0	199	25,764	194	24,222
Wikihouse Skylark brick cavity wall	26,556	1,389	2,715	12,768	374	753	6,350	78	50,983

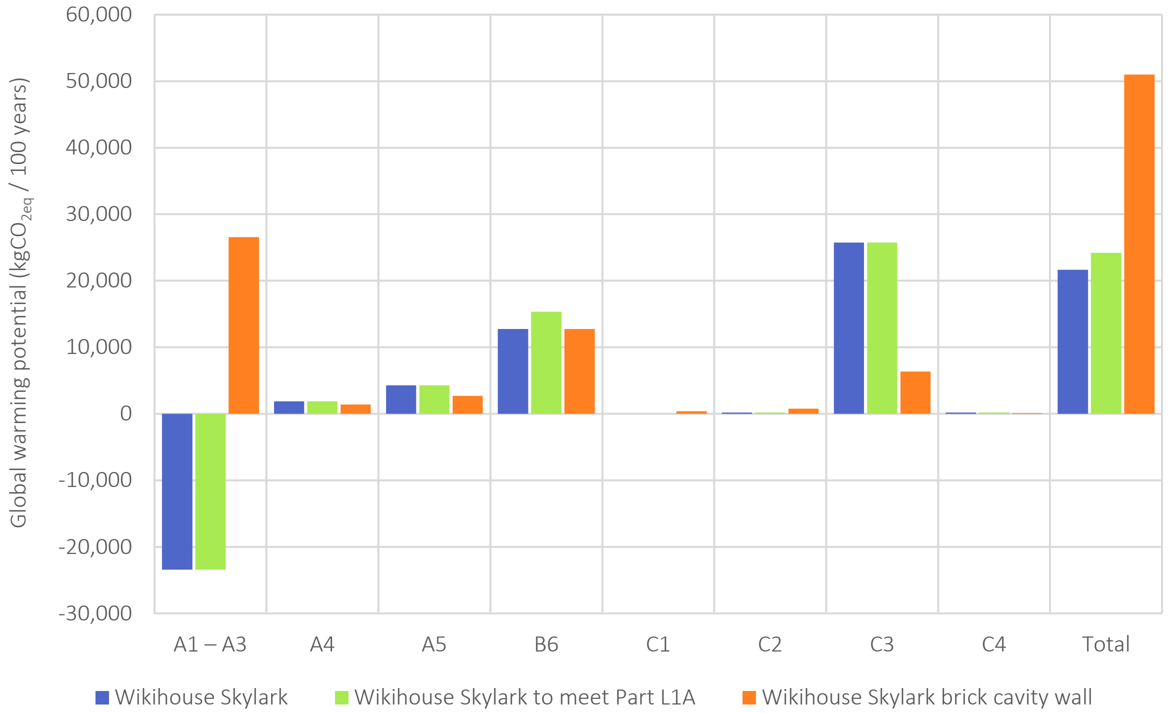


Figure 3.3 Balance of life cycle emissions for Wikihouse Skylark dwellings

Based on this assessment, it can be observed that the global warming impact of the cavity wall house during its lifetime (100 years) is more than 4.3 times the Wikihouse building, excluding the impact of the operational emissions (B6), which, when included decreases this ratio to 2.4 times. The Wikihouse dwelling built to meet Part L1A fabric standards does however have a similar life cycle impact to the Wikihouse with the target performance defined in section 2, apart from its operational emissions. When built to meet the fabric standards of L1A, in use emissions increase by approximately 3000 kgCO$_2$.eq, which further emphasises the significance of the embodied carbon in the overall LCA.

3.5 Interpretation

The results show that the WIKI house had less than half the lifetime emissions compared to the conventionally constructed house. This is mostly due to timber and the Wikihouse being much simpler to deconstruct and reuse. The negative emissions reported at the product stage (A1-A3 module) of the Wikihouse building are due to the stored carbon in wood products.

At some stage beyond the 100 years of the is assessment the carbon in the timber will eventually decompose release the same amount of CO_2 it absorbed during its lifetime into the atmosphere. Thus, if one ignored the sequestered carbon in wood products, the lifetime CO_2-eq emissions increase to 68,216 kg and 57,194 kg for the Wikihouse building and cavity wall house, respectively. Under these assumptions the Wikihouse performs worse than the cavity wall house, since the production of wood has relatively high embodied emissions, though this is outside of the system boundary of this assessment.

An additional complexity surrounding the life cycle emissions of timber is that when incinerated at the endo of its life, in an energy from waste plant, it can offset electricity produced by more carbon-intensive fuels. However, given the scope of this analysis is 100 years, by this time, decarbonisation of the national electricity grid will have taken place. Thus, burning wood to generate electricity in 100 years would no long offset carbon-intensive alternatives, as all grid electricity may be assumed to be zero carbon anyway.

Where timber is reused or downcycled (e.g. making wooden furniture out of structural timber, rather than burning it for energy recovery) the emissions from these secondary uses may be considered to offset the use of other virgin resources, however, accounting for this was beyond the scope of this assessment.

The emissions embodied in the materials used to make the houses, were much more significant than the total lifetime operational emissions of the homes; this was in part, due to the decarbonisation of the UK electricity grid. Having a future zero carbon electricity grid reduces the importance of reducing operational energy in this LCA. Thus, house builders looking to reduce the life cycle carbon emissions of their homes may instead focus on both using materials with low embodied carbon and reducing the embodied emissions of their deconstruction processes (i.e., design for deconstruction), above attempts to reduce their operational emissions to zero.

This may not, however, be the case for new homes that have not minimised their space heating demand. In addition, this finding may not translate to other nations where roadmaps to decarbonisation do not exist. No emissions associated with the decarbonisation of the UK electricity grid have been accounted for in this assessment as there is no clear allocation method for this. Thus, decarbonisation is considered free from emissions, for the purposes of this assessment, though there will be impacts of this national effort.

Other issues such as transport were found to not be hotspots in this LCA and are, as such, did not warrant a sensitivity analysis to investigate how different options may affect the LCA.

A sensitivity analysis was performed to investigate specific queries the Wikihouse team have concerning the overall impact of its design decisions relating to glazing choice, specifying double or triple glazing. For this purpose, double and triple glazed windows from the same source (QKE - EPPA) are used to maintain uniformity [59, 68]. The dimension of both window types is 1.23 m x 1.48 m. The LCA revealed that using triple-glazed windows result in emitting 5,824 kg CO_2-eq, while the equivalent double-glazed windows emit 4,370 kg CO_2-eq during the lifetime of the buildings. The LCA therefore suggests the benefit of upgrading to triple glazing so would be marginal, and so this is not recommended as a cost-effective way to reduce life cycle carbon emissions.

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