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Methodology to Quantify Cooling Demand in Typical UK Dwellings

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ABSTRACT

As per the 2020 UN emissions report, the average global temperature will increase by 3°C compared to pre-industrial levels if no corrective measures are taken and, with this, the frequency and intensity of heatwaves will also increase. Such a temperature rise will lead to an increased cooling demand. Although cooling provision may exist in commercial and industrial premises, this may not be the case for households. This paper presents a methodology to quantify the cooling demand of typical UK dwellings in a warming world. The commercial software IES VE was adopted, and white box modelling was carried out based on a literature review of construction standards and methodologies. Model verification was conducted to ensure compliance with building standards—allowing for a high degree of confidence in the modelling approach and methodology to understand and quantify future cooling demand.

Keywords: cooling demand, buildings, climate change

NONMENCLATURE

Abbreviations	
ACH	Air Changes per Hour
EPW	Energy Plus Weather
MAE	Mean Absolute Error
Symbols	
R	Resistance (K/W)
t_i	Thickness (m)
k_i	Thermal conductivity (W/m-K)
U	U-value (W/m²-K)
Q	Heat transfer (W)
A	Area (m²)
ΔT	Temperature difference (K)
R^2	R^2 score
y_i	Measured or observed value (W)
$\hat{y}_i$	Predicted value (W)
$\bar{y}$	Mean value (W)
n	Number of data points

1. INTRODUCTION

In the UK, without governmental strategy and regulations in place, an increased cooling demand from rising ambient temperatures will cause a knock-on effect on electrical distribution networks as residents begin to install (active) mechanical cooling solutions [1]. National Grid, the largest electricity transmission and distribution company in the UK, estimates that this additional cooling demand could place an excess 39 GW of peak electricity demand upon the network by 2050 on typical summer weekend days [2]. This does not consider the additional demand on extremely hot days during heatwaves. When compared to the current spare capacity of 76.6 GW available in the UK network [3], the additional load on atypical days will use more than half the spare capacity available.

The British government has introduced measures to combat overheating risks through Part O of the Building Regulations [4]. This ensures new constructions in the UK conform to the CIBSE TM59 standard (overheating risk assessment) [5]. It encourages architects and engineers to focus on incorporating passive strategies into the design stage of dwellings and carry through until the building has been constructed. The standard, whilst encouraging, has an important drawback in that it does not account for overheating in existing dwellings that currently make up most residential properties.

Although a detailed dataset on UK cooling energy consumption is available, this is restricted to the non-domestic sector [6]. Understanding how households and domestic buildings respond to extreme heat and how this might create greater demand for space cooling is yet to be determined [7]. This paper contributes to bridging this gap by presenting a methodology to estimate cooling demand for typical UK dwellings in a warming world. The methodology allows users to obtain the indoor temperature of common dwellings using custom scenarios. With this, simulations can be carried out to model the effect of heatwaves and other weather events and thus estimate indoor conditions and the cooling load

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of households. With the assumption that residents will use active cooling above certain indoor temperatures, this in turn enables quantifying the cooling demand that will be placed on the electricity grid using different cooling technologies (such as reversible heat pumps and portable air conditioners).

Based on a literature review of UK construction standards and methodologies applied for the past 100 years alongside the construction plans of the most common dwelling types, dynamic thermal models for the dwellings were created using the modelling software IES VE [8]. This software was selected to ensure compliance with global building standards such as CIBSE and ASHRAE, with which the in-built modules of the software have been already validated. The methodology for dwelling modelling was additionally verified against existing data for a semi-detached building available in the literature in [9]. This allowed for a high degree of confidence in the modelling approach—leading to an effective calculation of cooling demand.

2. BACKGROUND AND LITERATURE REVIEW

2.1 UK housing stock

A review of the current housing stock was carried out to determine both the constructions and designs of a large proportion of the dwellings within the UK. The initial step was to obtain the average age of households.

Fig. 1 shows the age of dwellings in England as determined by a housing survey in 2020 carried out by the Department for Levelling Up, Housing and Communities [10]. Most households were constructed before 1965. Building Regulations were introduced in 1965 to ensure the health and safety standards within buildings. These regulations established performance benchmarks for fire protection, egress, and building thermal efficiency [11].

Within the regulations, the thermal transmittance values, or U-values, are essential as they enable the quantification of the materials' thermal efficiency using a standardised methodology allowing for comparisons between different compositions. They indicate the rate at which heat transfers through a given material (which can be composite) [11]. Thus, the higher the U-value is, the greater the rate of heat transfer is through the structure for each construction (e.g. walls, roofs, windows, and floors). The U-value for the building envelopes in households post-1965 can be extracted from each new iteration of the UK Building Regulations.

The calculation of a U-value is shown next for completeness. The resistance of a material or composite wall is calculated using

$$R = \sum \frac{t_i}{k_i} \tag{1}$$

where i refers to the individual material in a composite structure, t_i (m) is the material thickness, and k_i (W/m-K) is its thermal conductivity. The thermal transmittance or U-value U (W/m²-K) of a material is then determined by

$$U = \frac{1}{R} \tag{2}$$

The rate of heat transfer Q (W) through the composite structure is obtained with

$$Q = UA\Delta T \tag{3}$$

where A (m²) is the surface area and ΔT (K) is the temperature difference between both sides of the wall or material (e.g. external and internal temperatures).

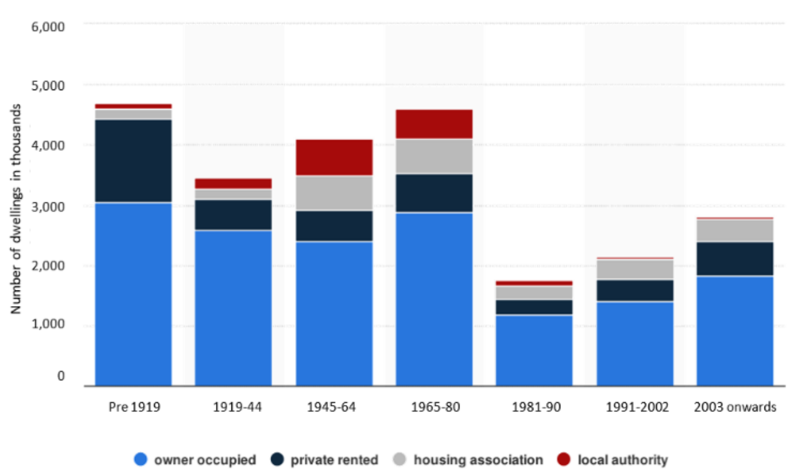

Fig. 1. Age of dwellings in England in 2020 by tenure [10].

2.1.1 Foundations

To determine the pre-1965 U-values for building foundations, the Building Act of 1878 implied that a 9 inch (225 mm) thick concrete foundation shall be placed on the ground unless the sub-soil is gravel or rock [12]. Thus, pre-1930s buildings have been assumed to have a foundation of 225 mm thick concrete.

Other methods including strip and raft foundations became popular in 1940-1950. However, these retained a concrete slab on top, and therefore, have been assumed to be the same until the 1960s. After this period, the UK Building Regulations came into effect mandating a minimum U-value for floors, which has been continuously updated in subsequent years.

Table 1 summarises the U-values for foundations throughout the years considered in this paper.

2.1.2 Walls

Reference [13] states that the minimum thickness sufficient to resist rainwater penetration in temperate climates is 315 mm for stone/brick walls. Thus, it was assumed that the minimum wall thickness for pre-1920s constructions is 315 mm as post-work modifications would have to be applied to thinner constructions to meet the building standards.

Starting with the post World War 1 housing boom, cavity walls became the most used construction method in the UK. These walls were more effective in keeping out rain and snow compared to single layered walls [13]. Thus, other types of walls have been disregarded in this paper. Table 1 shows relevant U-values for walls.

2.1.3 Windows and Doors

As specified in [14], new quality windows should last between 15 to 20 years. With many companies offering warranties for up to 25 years, it was assumed that most households would not have any windows older than 30-35 years. Doors also have an expected life span of 20 to 25 years for unplasticised PVC doors and 30 years for composite and timber doors [15]. Therefore, it was assumed that doors should not be older than 30-35 years. Further to this, the UK Building Regulations classify windows and doors in the same category for the maximum allowed U-values [11]. A summary of U-values for windows and doors is shown in Table 1.

2.1.4 Roofs

Throughout the years, the UK government has provided many grants that allowed homeowners to install loft insulation free of charge in their homes to reduce energy wastage. With the ease of installation and the availability of grants, it was assumed that most households would have upgraded their loft insulation within the last 30 years. This assumption enabled to extract roof construction data from the UK Building Regulations. The consolidated data for roof construction is shown in Table 1.

Table 1. Summarised construction data.

Year	**U-value (W/m²-K)**			
	Foundations	**Walls**	**Windows/Doors**	**Roofs**
Pre-1920	225 mm concrete slab (≈ 3.25)	Single layered brick /stone 315 mm (≈ 1.84)	N/A	N/A
1920	-	Uninsulated cavity walls (≈ 1.6)	N/A	N/A
1930	300 mm concrete slab (≈ 2.94)	-	N/A	N/A
1965	Thermal insulation on slab (1.2)	Uninsulated cavity walls (1.7)	N/A	Insulated Roofs (1.6)
1970	-	-	Single glazed window (4.8)	
1980	-	Insulated cavity walls (1)	-	Insulated Roofs (0.68)
1990	-	Insulated cavity walls (0.6)	-	Insulated Roofs (0.4)
2000	Thermal insulation on slab (0.51)	Insulated cavity walls (0.45)	Double glazed window (3.1)	Insulated Roofs (0.35)
2010	Thermal insulation on slab (0.22)	Insulated cavity walls (0.3)	Low emissivity double glazed window (2.0)	Insulated Roofs 0.22)
2016	Thermal insulation on slab (0.13)	Insulated cavity walls (0.18)	Double glazed low emissivity window with Argon gas filler (1.4)	Insulated Roofs (0.13)
2021 onwards	Thermal insulation on slab (0.13)	Insulated cavity walls (0.18)	Double glazed low emissivity window with Argon gas filler (1.2)	Insulated Roofs (0.11)

2.1.5 Dwelling design selection

According to the housing survey in [10], which determined the percentage of dwelling types by tenure, the most common are terraced, semi-detached, detached, bungalows, and flats. Using this information with publicly available floor plans such as in [16], it is possible to create three-dimensional models of all the above-mentioned house types. An example of such a model generated using IES VE is shown in Fig. 2.

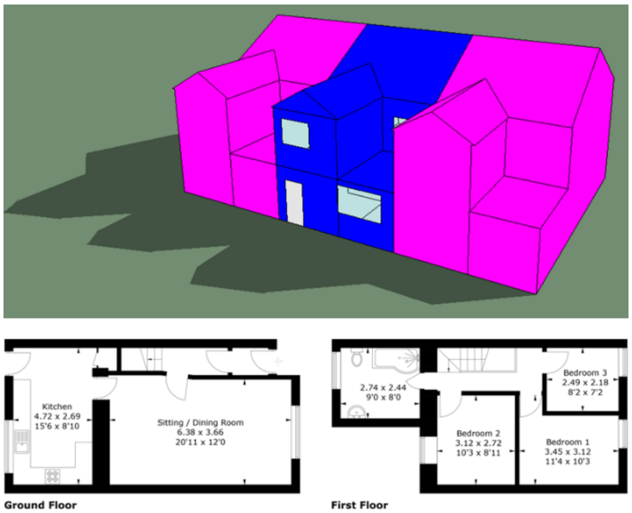

Fig. 2. Three-dimensional model of a terraced house generated in IES VE using a layout obtained from [16].

As shown in Fig. 2, certain dwelling types have multiple configurations to account for. Terraced houses are divided into end and middle houses depending upon the location within a row of houses. This will have major impacts upon the thermal envelope loads. Thus, both house types must be modelled. This also applies to flats, so modelling must cover middle or corner flats and ground, middle floor, or top floor flats.

2.2 Modelling approach

Numerical models for building energy simulations can be classified as black box, white box, and grey box models. Black box models are used when there is no data available on the building design or construction. It makes use of historical load data such as boiler energy usage to assess energy performance. White box models use known input parameters (constructions, designs, and weather) to simulate the thermal loads and predict the reactions to scenarios with detailed modelling. Grey box models are combinations of white and black box models. This paper adopts a white box modelling approach.

2.2.1 IES VE

IES VE is a commercial building modelling software designed to simulate building loads (and management) to calculate the energy demand during the design stage of construction projects. As it is widely used in industries, it was adopted in this paper as it conforms to various worldwide standards (e.g. ASHRAE 140, CIBSE TM33)—ensuring the accuracy and reliability of the simulations.

2.2.2 Verification of the numerical model

Reference [9] presents a comparison of dynamic thermal models of dwellings in Loughborough, UK, using synthetically occupied test houses. The work involved monitoring the internal temperatures during summer of the two mirrored but identical semi-detached houses shown in Fig. 3 (termed for simplicity East house and West house). Electrical gains were induced to capture the internal heat gains from miscellaneous and occupant loads. The house windows were kept closed. The internal and external temperature conditions were monitored during 3 weeks in 1-minute intervals.

(a) (b)

Fig. 3. Houses adopted from [9] to verify the numerical model in IES VE: (a) front; (b) rear.

Using IES VE, the houses and the surrounding areas were modelled, as shown in Fig. 4. The input weather files for the model were updated to match the conditions recorded during the testing period.

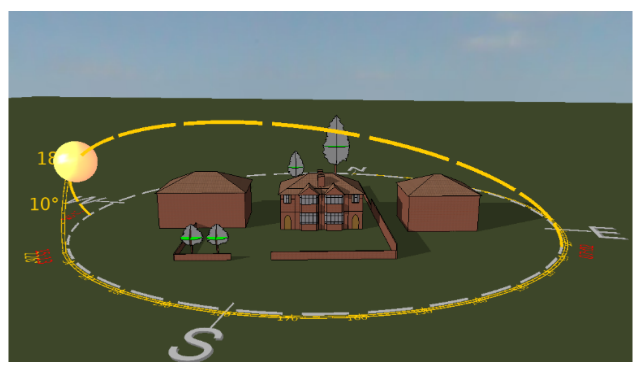

Fig. 4. Houses in [9] modelled in IES VE

The natural ventilation rate was calculated for both dwellings using blower tests. A fan was sealed into an external door with no air gaps and all external doors and windows were shut. The fan blew air in and out of the building, thus inducing a pressure difference between indoors and outdoors. The pressure difference was set to 50 Pa and the air flow rate to maintain such pressure differential was then measured.

The measured air changes per hour (ACH) at a pressure difference of 50 Pa were 15.3 for the West house and 15.6 for the East house. However, a typical practical pressure differential is closer to 7.3 Pa [17] and, thus, the measured ACH must be scaled down to obtain the natural ventilation rate. A common method to achieve this consists of dividing the measured ACH by an arbitrary value between 10 and 30. Taking the East dwelling as a reference, the model was run multiple times with natural ventilation rates 15.6/20 = 0.78 ACH, 15.6/30 = 0.52 ACH, and a lower value of 0.35 ACH, with the most accurate results obtained with 0.35 ACH. This is a meaningful outcome as the UK Building Regulations Part F states that less airtight dwellings can be assumed to have an infiltration rate of 0.15 ACH [18]. With such a consideration, the dwellings under study, which were constructed in the 1930s, were assumed to have a higher air exchange rate than less airtight dwellings.

Energy Plus Weather (EPW) files can be read by IES VE to incorporate weather data for the dwelling models. For the model verification conducted in this paper, the EPW file was converted to a CSV format and the data was manually adjusted to align with the recorded weather data for the time of the reference experiments in [9]. This was then reconverted back into an EPW format to be read by IES VE. This allowed for the precipitation, solar radiation, temperature, and cloud cover data to be used for the simulation of the dwellings.

Although in [9] the houses were considered as mostly empty, the effects of furniture on indoor temperatures must be accounted for. This is because the additional thermal mass of furniture can have a significant impact on the local indoor humidity and thermal comfort [19]—as furniture absorbs heat from the warm air and the solar radiation gains (if near a window) and releases this heat slower than the air naturally does. Using IES VE's Furniture Mass Factor (set to 1), an additional thermal mass was assigned within the rooms to absorb heat when the room was warmer than the furniture and release it for reverse conditions.

Internal gains due to occupants, equipment, and lighting were all accounted for during the experiment in [9] and this information was used for the software verification conducted in this paper. The experiment used heaters on regular schedules to simulate occupancy within the dwelling. This heating schedule was applied within IES VE to account for the additional heat gains caused by the occupancy pattern.

Both houses were simulated in IES VE. However, only the control test (East dwelling) was used for model verification as the opening and closing of windows were not simulated. The simulated indoor temperatures, alongside the measured temperatures in [9] for the rooms that were monitored are presented in Fig. 5.

As shown in Fig. 5, the results obtained with IES VE closely resemble the experimental data. To quantify the

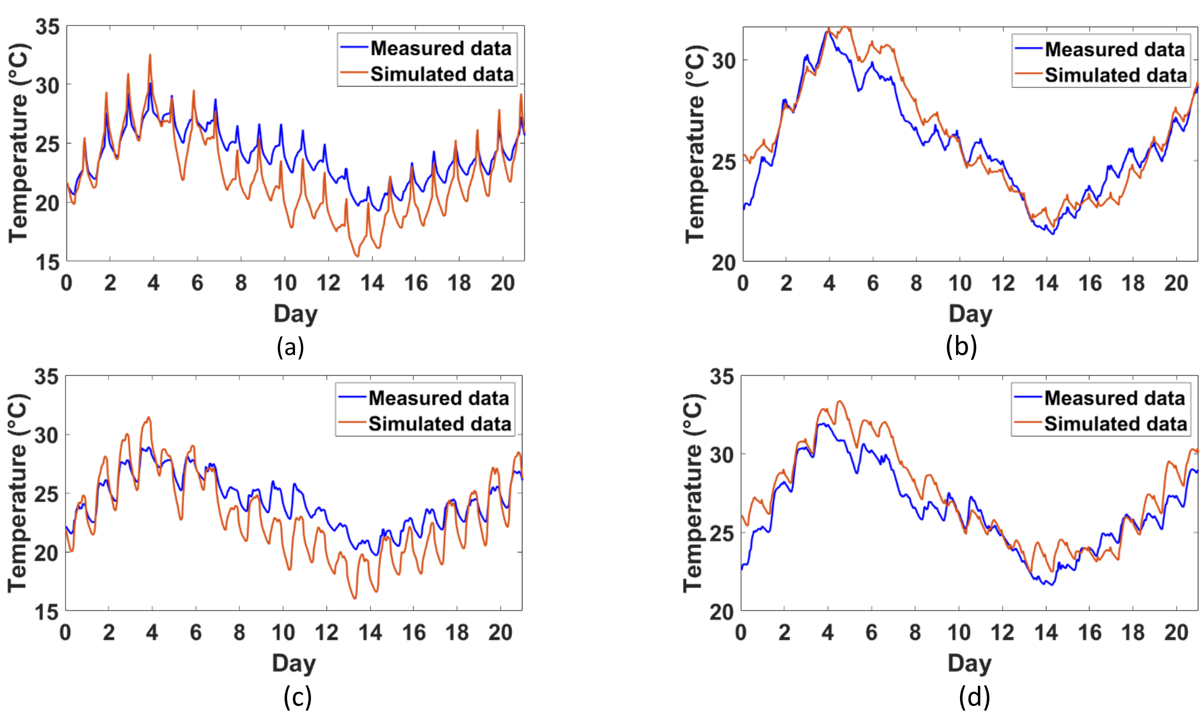

Fig. 5. Comparison of internal room temperatures using IES VE with measured values reported in [6]. (a) Kitchen. (b) Rear bedroom. (c) Living room. (d) Front bedroom.

difference between the two sets of results, two accuracy metrics were used. The first one is the R^2 value. This characterises the performance of regression models by measuring the proportion of the total variation in the simulated values that can be explained by the measured data (independent variables). It is defined as:

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2} \quad (4)$$

whereby y_i stands for the measured or observed value, $\hat{y}_i$ stands for the predicted or simulated value, and $\bar{y}$ is the mean value of y.

The other accuracy metric used is the mean absolute error (MAE), which determines the magnitude of difference between the values obtained from measurements and simulations. It is defined as:

$$MAE = \frac{\sum|y_i - \hat{y}_i|}{n} \quad (5)$$

whereby y_i stands for the measured or observed value, $\hat{y}_i$ stands for the predicted or simulated value, and n is the number of data points.

The results for both metrics are shown in Table 2.

Table 2. R^2 and MAE (in °C) for the simulated and measured results.

	East House				
	Living room	Kitchen	Front bedroom	Rear bedroom	Single bedroom
R^2	0.87	0.84	0.90	0.91	0.85
MAE	1.68	1.99	1.10	0.73	1.22

An average R^2 value of 0.87 for the house was obtained, which indicates a strong agreement of the simulated results with the experimental data. The average MAE between the simulated and experimental results was 1.34°C. These metrics, alongside the visual representation in Fig. 5 showing good agreement, demonstrate that dwelling models in IES VE provide reliable and accurate results.

3. METHODOLOGY FOR COOLING DEMAND ESTIMATION

3.1 Generating datasets

The methods presented in Section 2.2 are useful to estimate the cooling demand for individual dwellings in the UK. To account for all the potential constructions examined in this paper, a model would need to be run for each combination of constructions in Table 1. This would mean conducting 6720 simulations (6 foundation types, 8 wall types, 5 window types, 7 roof types, and 4 orientations) for each type of dwelling. Such a detailed exercise is out of the scope of this paper and instead a couple of specific examples are provided in Section 4.

A discussion is provided next on how to reduce the number of simulations per type of dwelling by removing the least likely scenarios. Such an approach may considerably reduce the computation time when generating an output dataset.

As per the housing surveys report 2021-2022, 87% of homes in England have installed double glazed windows [10]—leaving 13% of homes with single glazing. However, as shown in Table 1, single glazed windows could not be installed into new homes or replaced in older buildings since 2000. Alternative solutions to double glazing are available such as secondary glazing, which consists of installing a separate discrete window between the external window and the room. This provision allows listed buildings with single glazing to meet the energy performance requirements for UK households. Thus, single glazed windows may be removed from the modelling process as they can no longer be installed.

Grants such as the Green Deal Home Improvement Fund, Home Upgrade Grant in England, Nest in Wales, and Warmer Homes in Scotland offer monetary support to improve loft insulation in UK households [20], [21]. It can be thus assumed that most dwellings will have had their loft insulation upgraded within the last 20 years and older loft insulation values may be removed.

Furthermore, for the dwellings constructed in the 1920's, U-values for uninsulated cavity walls were approximated to be 1.6 W/m²-K. With the introduction of the Building Regulations in 1965, the maximum allowed U-value was 1.7 W/m²-K. As the 1965 standard provides a higher value, it can be adopted for modelling.

Dwellings sharing walls with adjacent properties (e.g. semi-detached, flats, terraced houses) have their thermal demand affected by the thermostat settings of the neighbouring properties. However, it is not possible to simulate the exact internal conditions of the adjacent buildings as these will vary widely from having identical conditions (matching set points for heating and cooling) to having an unoccupied dwelling with no heating or cooling applied. For simplicity, the adjacent spaces could be modelled as unconditioned spaces.

3.2 Locational data

The weather and solar radiation distribution vary considerably throughout the UK, as evidenced by the photovoltaic power potential map shown in Fig. 6. To consider a different band of solar radiation levels, two locations were selected: Cardiff and Manchester.

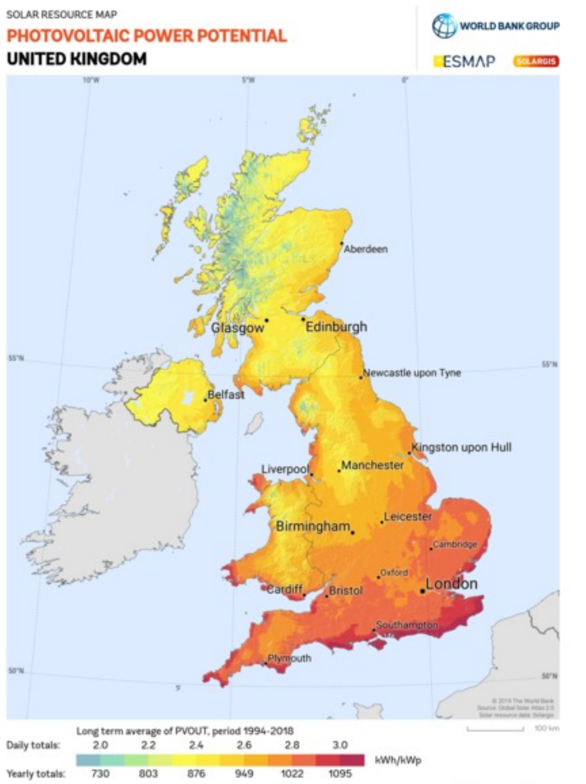

Fig. 6. Photovoltaic power potential in the UK [22].

It should be highlighted that the energy demand for a dwelling will be affected by additional heat gains from equipment loads (e.g. TV, cookers, laptops), occupants, and lighting. The energy from these heat sources may fluctuate considerably between dwellings. Creating a standard internal thermal load for each case is thus not feasible. However, these loads will always be positive and can be defined at a later stage to be applied to the simulated data. This way, it is possible to assess custom scenarios to account for varying schedules (e.g. indoor activities in the evening or night hours).

4. RESULTS AND BRIEF DISCUSSION

Using the methodology presented in Section 3, the thermal energy demand for a detached house and a mid-terraced house in Cardiff and a ground floor flat in Manchester were obtained for a design year. The design year was created by Climate One Building [23] by selecting a span of years and selecting a month's worth of data from each measured year.

The demand profiles are shown in Fig. 7. Negative values represent the cooling demand of the dwelling and positive values refer to its heating demand. The results indicate that energy demand will be significantly affected by the type and location of each dwelling—as expected. For instance, the peak cooling demand of the detached house in Cardiff (see Fig. 7a)) is approximately two times larger than that of a mid-terraced house in the same city (see Fig. 7(b)), which in turn is two times larger than that for a ground floor flat in Manchester (see Fig. 7(c)).

These results demonstrate the utility of the modelling methodology in identifying and quantifying the variations in cooling demand across different house types and locations as well as for different times of the year within the same house.

5. CONCLUSION

This paper presented a methodology to estimate the cooling energy demand for the most common type of dwellings in the UK housing stock. To consider most of the existing dwellings, a comprehensive literature review of the UK building constructions throughout the last century was conducted.

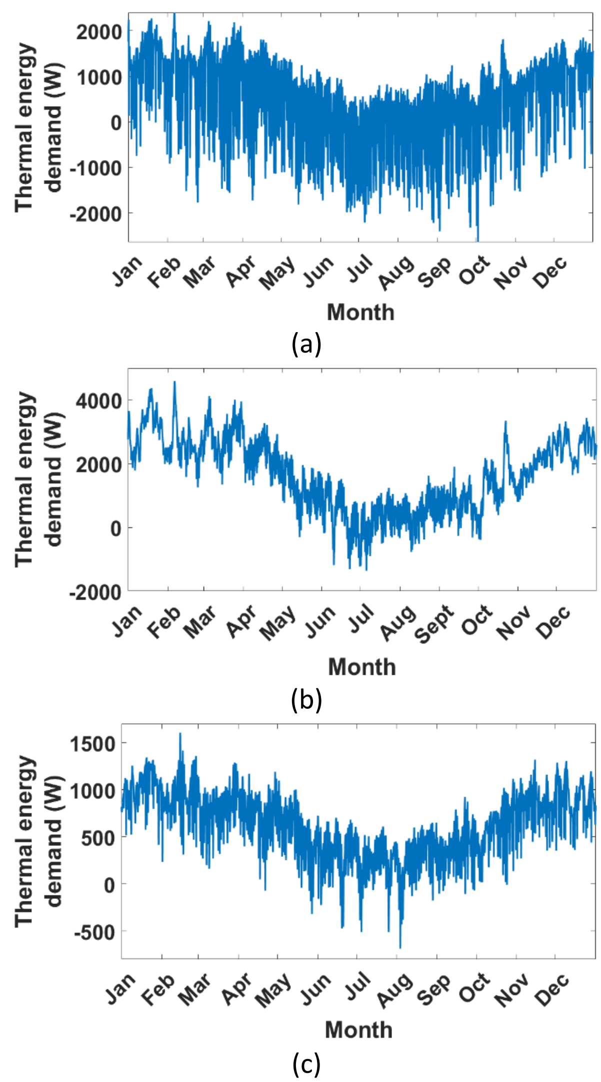

Fig. 7. Results showing the thermal energy demand for (a) a detached house in Cardiff, (b) a mid-terraced house in Cardiff, and (c) a ground floor flat in Manchester.

An approach to determining the heating and cooling demand of any dwelling was outlined. This only requires basic information of the building (i.e. age of the building and date of last renovations). The temperature set points are also accounted for with a method to calculate the variation in energy demand arising from a change in the indoor set point temperature. This allows users to adjust the temperature to their preferred settings while being aware of the impact of their decisions on household energy expenses.

The methodology presented in this paper may be adopted to aggregate the cooling demand from households to calculate the total thermal energy demand for communities. This can be translated to electrical energy requirements when using different cooling technologies such as reversible heat pumps, split air conditioners, and portable air conditioners. In turn, the suitability of the grid infrastructure to meet cooling demand can be explored in specific geographical locations. Combining this with predicted weather data for a given location, the presented work may be extended to determine the future cooling load of dwellings and the associated increased electrical demand on electricity networks.

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