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Planning energy interventions in buildings and tackling fuel poverty: Can two birds be fed with one scone?

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ABSTRACT

Energy retrofitting and renovations are an inseparable part of decarbonisation strategies in the building sector. These measures are often tied up with several social factors that can potentially impact the wellbeing of households and the community if the end-user requirements are not carefully considered. Fuel poverty is one of these social factors that is an essential consideration for designing effective, just, and user-centred interventions, but it is often overlooked in engineering processes. Therefore, this article seeks to re-connect the notion of fuel poverty to practice by bringing it forward from the post-intervention assessments to the design and decision-making stages. To do so, a new indicator, Potential Fuel Poverty Index (PFPI), is developed to obtain the likelihood of fuel poverty that future interventions can pose to the households. The PFPI presents a more targeted analysis of fuel poverty by reflecting the socio-spatial characterisation of the households. Using the PFPI, fuel poverty can be observed as a design/decision factor at the early stages of sketching interventions, in conjunction with other economic, environmental, and technical factors. Finally, the utility of the developed method is demonstrated using a real case study in the UK, assessing the impact of heat decarbonisation through heat pumps on fuel poverty.

Abbreviations

AHP	Analytic hierarchy process
ASHP	Air-source heat pump
DHW	Domestic hot water
EPC	Energy performance certificate
GHG	Greenhouse gases
HEP	Hidden energy poverty
LCA	Life cycle assessment
LCC	Life cycle costing
LIHC	Low income high cost
LILEE	Low income low energy efficiency
MCDA	Multi-criteria decision analysis
MCDM	Multi-criteria decision making
MEPI	Multidimensional energy poverty index
PFPI	Potential fuel poverty index
SA	Sustainability assessment
SCoP	Seasonal coefficient of performance

Nomenclature

E	dimension of vulnerability related to the energy use
ECT	energy cost threshold
EDI	equivalised disposable income
EEC	equivalised energy cost
F	dimension of financial vulnerability related to fuel poverty
F^s	dimension of financial vulnerability related to severe fuel poverty
PT	poverty threshold
SPT	severe poverty threshold

1. Introduction

The growing threats of climate change and the urgency of sustainable

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transitions toward low-carbon societies are now well underway across the world [1]. In this context, the role and importance of the residential building sector, as a major contributor to the climate crisis, is widely acknowledged in research and policy landscapes [2]. In the UK alone, according to 2020 figures, the final energy demand of the residential sector is 39.3 Mtoe, making up 32 % of the UK's final energy consumption [3]. Residential buildings are also responsible for nearly 23 % of the country's total direct and indirect carbon footprint [4]. The figures clearly remark the necessity of a low-carbon energy transition in this sector in order to put the country on a path to a net-zero emission economy.

Energy retrofits and renovations in the building stock, generally referred to as building energy interventions in this paper, are broadly recognised as key components of energy-saving and CO_2 mitigation strategies in the building sector [5]. This is more emphasised in the UK where around 57 % of the homes are built before 1965, making it one of the countries with the least energy-efficient housing stock in Europe [6]. However, the UK government has made an ambitious target to fully decarbonise the building industry by 2050 under the Climate Change Act 2008, surpassing the EU's respective targets [7]. Along this pathway, it is estimated that 29 million existing homes across the UK require retrofitting [8]. This pathway is clearer structured in the Heat and Buildings Strategy [9] by setting out a set of action plans such as phasing out the installation of fossil fuel heating systems in off-gas-grid homes from 2026 and in on-gas-grid properties from 2035.

Building energy interventions are often intertwined with several social factors that could potentially impact the wellbeing of people and communities [10,11]. These factors are often investigated under the theme of "social sustainability" in academic and policy discourses [12–14]. The core idea of social sustainability among its different definitions in the literature targets the interactions of a process with the health, safety, and wellbeing of current and future generations [15]. However, a consistent understanding of how to specify and measure social sustainability concerning building interventions is still lacking in both academia and practice [15–17]. Despite the well-established frameworks for the economic and environmental assessment of building interventions, social sustainability is less often discussed and, consequently, less addressed in design and planning stages [18–21].

Addressing this gap exposes a need for more holistic approaches which can bridge the three pillars of sustainability -economic viability, environmental protection and social equity- in an integrated framework [22]. In this respect, multi-criteria analysis methods, such as sustainability assessment (SA) [23,24] and multi-criteria decision analysis (MCDA, also known as Multi-Criteria Decision Making, MCDM) [25,26], have been increasingly used in the building industry to represent the complexities within the systems and explore the trade-offs between various criteria [27]. Considerable research can be found applying these methods to building intervention [27–31]. However, it is found and discussed in this paper that social factors are less well understood even in multi-criteria analyses [32,33].

Fuel poverty is one of the main indicators of social sustainability that is often overlooked as a criterion associated with building energy interventions [34]. The existing multi-criteria analysis frameworks do not usually take into account the risk of fuel poverty that may be encountered as a result of implementing intervention scenarios. Understanding the linkage between fuel poverty and these scenarios is of vital importance for designing effective, fair, and sustainable solutions. Thus, a new method is proposed to provide an evaluation of fuel poverty under the circumstances of future building energy interventions. The developed method can complement the current multi-criteria analyses by incorporating fuel poverty as a design/decision factor into MCDA and SA frameworks, helping to untangle the synergies and trade-offs between fuel poverty and other influencing factors. This will lead to more informed and accurate intervention solutions, aiding decision makers to tackle this social disparity before it arises using a preventive approach.

This paper is structured along the following sections. Following the introduction in this section, Section 2 reviews the literature to explore the current role of fuel poverty in planning and assessing building energy improvement scenarios. In Section 3, the proposed method of this research is elaborated. Section 4 presents the results from the application of the proposed method to the selected case study and discusses its main contributions. Finally, the main findings, limitations, and conclusions that can be drawn from this research are summarised in Section 5.

2. Fuel poverty, a missing factor in multi-criteria analyses

Bouzarovski and Petrova [35] have provided a general definition that underpins all different forms of energy and fuel poverty, "The inability to attain a socially and materially necessitated level of domestic energy services". This is more often referred to as fuel poverty in the UK where it has a long history in academic and policy discourses [35]. Fuel poverty is recognised as a global concern and a rapidly growing agenda for policymakers and practitioners [36]. Based on an EU-wide survey in 2020, around 8 % of the EU population were unable to access or afford adequate indoor thermal comfort in their homes [37]. This problem is more pronounced in the UK, where about 4 million UK households (15 % of all households) were estimated to live in fuel poverty in the same year [38].

Fuel poverty is typically driven by energy-inefficient buildings, high energy prices, and low income, resulting in either cold indoor temperatures or sacrificing other essentials, such as food and health services, to afford adequate warmth [36,39]. This can cause several detrimental effects on households and society [40]. Perhaps the most significant effect is on physical health with a close correlation between excess winter deaths, cardiovascular disease, and respiratory problems [41]. Fuel poverty has also been closely linked to mental and social health issues such as social isolation and anti-social behaviour, more severely in children and the elderly [41,42].

Previous research has suggested that building energy interventions are one of the most effective ways to alleviate fuel poverty, while accelerating the transition toward low-carbon buildings [39]. However, capturing the synergies between fuel poverty alleviation and building energy interventions requires more holistic approaches to better understand their potential interferences [43]. While several studies have attempted to examine the interactions between fuel poverty and energy retrofits in buildings, no certain mechanism has been established to estimate the risk of fuel poverty under the conditions of future initiatives [11,44,45]. Existing literature reveals that only a few studies, such as [46,47], have adopted a predictive approach to estimate the risk of fuel poverty in dwellings that have not been built or policies that have not been implemented yet. Abbasi et al. [21] recently elaborated on this gap, signifying that pre-intervention assessments are less sensitive to social factors, namely fuel poverty, as they are primarily aimed at minimising the cost and emission factors.

This gap has consequently led to limited attention to fuel poverty as a design or decision factor in engineering discourses [48,49]. Table 1 presents a list of some of the recent multi-criteria analysis studies dealing with building energy interventions from an engineering point of view. None of the reviewed studies has considered fuel poverty as one of the assessed social criteria. In a broader sense, this table confirms that social aspects tend to be excluded from the research compared to the economic and environmental terms, underpinned by several scholars [27,28,33]. In a recent review by Hashempour et al. [28], it is shown that in only 22 % of the frameworks, social dimensions are considered in the analysis of sustainable renovations, usually limited to indoor air quality, functionality, job creation, thermal comfort, and social acceptance [33,50]. In contrast, energy interventions have been often motivated by CO_2 emission reduction, energy saving, investment cost, and operation and maintenance costs [11,51].

The exclusion of fuel poverty from engineering processes can be attributed to several reasons. In the first instance, fuel poverty is widely recognised as a complex societal challenge in the existing body of

Table 1
Methods and criteria used for evaluation of building interventions in multi-criteria studies.

Focus of the study	Comparative analysis method	Assessment factors	Analysis/Decision criteria	Source
Energy conservation measures in residential buildings	LCC	Economic Environmental	Life-cycle costs, initial cost Annual energy consumption	[52]
Energy efficiency measures in new commercial buildings	LCC & LCA	Economic Environmental	Life-cycle costs, internal rate of return life-cycle carbon emissions, carbon costs	[53]
Office buildings' envelope	Multi-objective optimisation using Harmony search algorithm	Economic Environmental Social	Life-cycle costs Life-cycle emission Thermal comfort index	[54]
Sustainable interventions in historic buildings	LCA & MCDM	Environmental	Annual energy consumption, life-cycle carbon emissions, emission payback period	[55]
Façades refurbishments for office buildings	LCA	Environmental	Yearly heating energy, life-cycle energy balance, life-cycle carbon balance, energy payback period, carbon payback period	[56]
Sustainable retrofit measures in residential buildings	Qualitative MCDM	Economic Environmental Social	Renovation cost, repair cost Waste generation, recyclability, Duration of works, needed space, adaptability, disruptions for inhabitants	[57]
Distributed electricity generation systems for residential buildings	MCDM using AHP and PROMETHEE	Economic Environmental	investment cost, running cost CO2 emissions, primary energy consumption	[58]
Household-level renewable heating technologies	MCDM using TOPSIS	Economic Environmental Technical	Energy bill, energy expenses reduction, initial investment, payback period, subsidy Greenhouse gas emission, use of renewable energy Performance, needed reparations, reliability, easy to use	[59]
Renewable micro-generation technologies in households	MCDM using TOPSIS, EDAS & WASPAS	Economic Environmental Technical Social	Technology cost, operating and maintenance costs, payback period CO2 emissions, land use Noise, technology maturity, technological improvement Distort the landscape, society appreciation, job generation, impact on the social progress, market stability, local & global market	[60]
Energy retrofitting measures for office stock	LCC & LCA	Economic Environmental	Life-cycle costs, annual economic savings, payback period Global carbon footprint	[61]

research, primarily falling under the remit of sociologists, economists, environmental, and scientists [35]. Researchers have often investigated fuel poverty with a diagnostic approach in post-intervention phases [62], using various subjective (also known as consensual or self-reported approaches; based on households' perception) and objective (based on measurements) methods [63]. The extensive research in this area has made significant advances in understanding the socio-economic context of energy deprivation and inequities. However, the multifaceted nature of fuel poverty entails hybrid ‘assemblages’, comprised of different inputs of energy, technology, society and physical capital, and environment [35].

The second possible reason can be found by looking at the technical drivers of fuel poverty, namely building efficiency and energy systems, which are always highlighted along with the demographic parameters [44]. The factor of building efficiency is paid increasing attention to as a crucial factor for identifying fuel poverty and, consequently, is gradually emerging in fuel poverty indicators. For instance, the new LILEE (Low Income Low Energy efficiency) indicator, set out by the UK authorities in 2021 to replace the LIHC in policy and legislation discourses, uses an absolute measure of energy efficiency [64]. However, the role of building energy systems is still marginalised in fuel poverty studies and indicators [35]. According to the authors, this is a gap in the literature where not all of the driving forces of fuel poverty are equally represented in the existing indicators. The technical nuances of fuel poverty cannot be precisely uncovered and addressed in solely social terms, but rather more holistic approaches are required to incorporate technological and engineering factors, expanding the traditional boundaries of fuel poverty scholarship [35,47]. This is somehow recognised in earlier studies, acknowledging the division between trajectories of recognition of fuel poverty and its driving forces, as well as highlighting the key role of technological factors in mitigating fuel poverty [35,62,65].

Reflecting on the mentioned research gaps and founded on the grounds set out in [21], this paper argues that fuel poverty should be brought forward from post-intervention evaluations to the design and decision-making processes. Observing fuel poverty drivers at the primary stages of projects could ultimately result in more informed, effective, and accurately targeted interventions. This exposes an opportunity to tackle fuel poverty through a predictive approach rather than the remedial approach which is taken in most instances to treat the present situation. The proposed method enables this shift by defining the Potential Fuel Poverty Index (PFPI) in a way that can be quantified, weighted, and incorporated into multi-criteria analysis processes. Using the PFPI, engineers and decision makers will be able to account for fuel poverty as a design/decision factor in conjunction with other environmental, economic, and technical parameters.

3. Proposed method

Drawing upon the gaps highlighted in the literature and the need for novel methods to incorporate fuel poverty in the design stages of energy interventions for buildings, a new method, is proposed in this section, the Potential Fuel Poverty Index (PFPI). The PFPI is developed to identify the impact of future building energy interventions on fuel poverty before implementing them. Furthermore, a case study is presented to assess the utility and potential capabilities of the proposed method in the assessment of intervention scenarios.

3.1. Calculation method

The PFPI is a two-dimensional objective indicator proposed to define fuel poverty based on the level of income and modelled energy cost at the scale of individual households. The proposed method is characterised as a predictive approach in which fuel poverty is identified based on the simulated energy cost rather than being based on actual spending. This approach is underpinned by the literature, acknowledging that required energy expenditure could better reflect the energy deprivation levels as it avoids the influence of individual preferences or customs such as “households' self-rationing” in low-income families or extensive energy needs of households with infirm or disabled members [66,67]. The advantages and disadvantages of this approach are further discussed in Section 4.3.

Therefore, in the first step, the total energy demand of the dwellings after implementing the energy interventions should be predicted using energy simulation tools and mathematical methods. Today, several sophisticated simulation tools, such as IES-Virtual Environment, DesignBuilder, and EnergyPlus are available to facilitate the complex calculations of buildings' energy performance [68]. These software tools can give highly accurate predictions as they take into account multiple factors such as weather, building material and thermal properties, occupancy conditions, heating and cooling systems, and home appliances, as long as the modelling and parameters setting are well performed [69]. Total household energy requirements include energy for space and water heating, energy for lights and appliances, and energy for cooking. The total energy cost can be obtained based on the current unit price of energy sources for business-as-usual analyses or based on the projected prices for life-cycle analyses of future scenarios.

Once the post-intervention energy costs are estimated, the likelihood of experiencing fuel poverty for the household with a certain range of income can be achieved using the PFPI indicator. The PFPI is adopted based on the subjective indicator of the Multidimensional Energy Poverty Index (MEPI) developed by Okushima [70,71] in 2019 and the objective indicator of Low Income High Cost (LIHC) developed by Hills [72,73] in 2012. In this method, the principles of fuel poverty measurement from the MEPI model are combined with the threshold determination and equivalisation rules from the LIHC. In other words, calculation instructions of the LIHC are utilised to determine the dimensions of the MEPI which is primarily devised to fit the Japan context. To comply with the predictive nature of the proposed index, simulated energy costs are employed instead of actual energy consumption used in [70] or the subjective assessment of the households' energy deprivation used in [71]. As a result, an objective version of MEPI, aligned with the principles of the LIHC standard, and applicable in the UK context, is developed. Combining fuel poverty evaluation methods has already been used and endorsed in a few studies, suggesting that the standalone methods may not be sufficient to make a holistic fuel poverty evaluation [71].

The proposed method also improves the LIHC instructions in terms of recognition of the household typologies in response to occupants' behavioural variations. Reflecting occupants' attitudes and preferences at the centre of energy retrofits is increasingly being adopted in the literature [74,75]. This approach helps target different groups of households more effectively and design interventions tailored to the demands of specific demographic groups [75]. Nonetheless, setting a single threshold for income and fuel cost at the national level, the LIHC indicator ignores the critical relationship between households' demands and their socio-spatial conditions.

Therefore, in the present method, the households are classified into four typologies (households with at least one person aged 65 years or over, households with at least one person with a disability, households in rural areas,[1] and other households) across twelve standard UK regions (Wales, Scotland, Northern Ireland, and nine England regions of North East, North West, Yorkshire and The Humber, East Midlands, West Midlands, East, Greater London, South East, and South West) so that they are not treated as a homogeneous group, facilitating more targeted measures. The government statistics by the Office for National Statistics (ONS) is the base from which this classification system is produced. The ONS presents the annual household disposable income and energy expenditure statistics broken down by four typologies identifiable on the basis of household composition across the country's standard regions [76]. Therefore, the required data corresponding to these typologies would always be available, which is critical for the verifiability of the proposed indicator.

The PFPI, therefore, defines fuel poverty and severe fuel poverty as the intersection of two dimensions of F_i and E_i as follows:

$$\text{Household } i \text{ is in fuel poverty} \Leftrightarrow F_i < 1 \wedge E_i > 1 \quad (1)$$

$$\text{Household } i \text{ is in severe fuel poverty} \Leftrightarrow F_i^s < 1 \wedge E_i > 1 \quad (2)$$

where F_i and F_i^s are the income dimensions, representing the financial vulnerability of the households in fuel poverty and severe fuel poverty, respectively. The E_i is the energy cost dimension, representing the vulnerability related to the energy use of the households. The parameters of F_i, F_i^s, and E_i can be obtained as follows:

$$F_i = \frac{EDI_i}{PT_{t_{(i)}}} \quad (3)$$

$$F_i^s = \frac{EDI_i}{SPT_{t_{(i)}}} \quad (4)$$

$$E_i = \frac{EEC_i}{ECT_{t_{(i)}}} \quad (5)$$

where *EDI* is the household's equivalised disposable income, *PT* is the monetary poverty threshold, *SPT* is the severe poverty threshold, *EEC* is the household's equivalised energy cost, and *ECT* is the energy cost threshold. The $t_{(i)}$ identifies the typology that household i belongs to. Typologies of the household in this study refer to the four aforementioned groups of households living across the standard twelve regions of the UK. Therefore, based on the PFPI definition, household i is classified as fuel poor or severe fuel poor if both income and energy cost dimensions apply.

The income dimension (F_i or F_i^s) represents the financial vulnerability of the household based on the household's equivalised disposable income (*EDI*). Disposable income is the available amount of money that households can spend or save after income taxes have been deducted. For a certain household, the income information of the occupants can be used. The household disposable income then should be equivalised to reflect the number of people in the households. This study follows the equivalisation procedure and uses the equivalisation factors (Table 2) provided by the LIHC methodology handbook where further details of calculations can be found [77]. To do so, the household's disposable income is divided by the sum of the relevant equivalisation factors to obtain the *EDI*. Generally, equivalisation increases the income rate for single people and decreases the income for larger families, intending to make them comparable. In case of unavailability of the household income data or for unknown future households, regional average incomes can be extracted from available databases. In England and Wales, the mean average equivalised disposable annual household income for local areas is available at [78].[2]

The *PT* and *SPT* are poverty and severe poverty thresholds for each household typology that are classified based on the composition of the households and their residence region. Following the prevailing definition of monetary poverty in Europe, the *PT* and *SPT* are set at 60 % and 40 % of the median for equivalised disposable income, respectively

Table 2
The income equivalisation factors for household members, according to the LIHC indicator [77].

People in the household	Income equivalisation factor
First adult in the household	0.58
Subsequent adults (including children aged +14)	0.42
Children under 14	0.20

[1] The classification scheme uses the Rural/Urban Definition by the UK government, defining areas as rural if they fall outside of settlements with a population of >10,000 residents.

[2] The database provides the average equivalised disposable annual household income at the Middle layer Super Output Area (MSOA) level in England and Wales for the financial year ending 2018.

[79–81]. The poverty thresholds are also equivalised to account for the number of people in each household. Table 3 presents the *PT*s and *SPT*s for different household typologies in the UK, calculated based on the UK National Statistics 2020 data [76].

The energy cost dimension (E_i) represents the energy vulnerability of the household according to the required energy cost. The *EEC* is the household's equivalised total energy cost required for achieving an adequate level of comfort after implementing an intervention, obtained from the software simulation. The simulated energy costs should be equivalised, similar to the income, by applying the relevant equivalisation factor for each household. To do so, the required energy cost is divided by the corresponding factor, which is recommended by the LIHC standard, given in Table 4. The equivalisation process for both income and energy costs is further explained in [77].

The *ECT* is the threshold for energy expenditure which equals the median of the energy costs for the household typology in the location of the study, equivalised to the average household size in the corresponding area. Household size refers to the number of residents (irrespective of age) living in a household [82]. The median equivalised energy cost is used in this study as the threshold, instead of 60 % of the median energy use in the initial MEPI method [70], to comply with the UK standards. The median energy costs of household typologies in UK regions based on the 2020 data can be found in [76]. To reflect the household size in the calculations, the energy expenditures are equivalised using the equivalisation factors given in Table 4 [77,83]. Dividing the median energy cost by the equivalisation factor (calculated based on the average household size in the regions), the *ECT*s can be calculated for each household typology. Following the described instructions, the *ECT*s for the UK application are calculated and shown in Table 5, based on the UK's energy expenditure data [76], equivalisation factors [77], and household size data [84].

The PFPI in this article is adapted to the UK context, so the associated thresholds are developed to be applied to UK-based case studies. The values of *PT*, *SPT*, and *ECT* are different in other countries and must be modified and recalculated based on the available data in that location.

The PFPI could be used as a binary indicator that, for a given household, indicates whether implementing a certain intervention is likely to result in fuel poverty or severe fuel poverty. Following Okushima [85], a binary identification function of $\rho(F_i, E_i)$ with two elements of income and energy cost can be set up in a way that $\rho(F_i, E_i) = 1$ when the household *i* is fuel poor and $\rho(F_i, E_i) = 0$ otherwise. Thus, the $\rho(F_i, E_i)$ can be defined as follows:

$$\rho(F_i, E_i) = 1 \Leftrightarrow F_i < 1 \wedge E_i > 1 \quad (6)$$

$$\rho(F_i, E_i) = 0 \Leftrightarrow F_i \geq 1 \vee E_i \leq 1 \quad (7)$$

Likewise, the identification function for severe fuel poverty can be defined similarly as follows, where $\rho(F_i^s, E_i) = 1$ suggests that the household *i* is exposed to severe fuel poverty and $\rho(F_i^s, E_i) = 0$ otherwise:

Table 4
The energy cost equivalisation factors for households, according to the LIHC indicator [77].

Number of people in the household	Energy cost equivalisation factor
One	0.82
Two	1.00
Three	1.07
Four	1.21
Five or more	1.32

$$\rho(F_i^s, E_i) = 1 \Leftrightarrow F_i^s < 1 \wedge E_i > 1 \quad (8)$$

$$\rho(F_i^s, E_i) = 0 \Leftrightarrow F_i^s \geq 1 \vee E_i \leq 1 \quad (9)$$

Accordingly, analysts and decision makers can predict if the household *i* is likely to be exposed to fuel poverty or severe fuel poverty after the building intervention had taken place. Although the PFPI is primarily defined in binary terms, it is also fit for indicating the intensity of fuel poverty as a scalar index. For this purpose, subject to fulfilment of the income criteria ($F_i < 1$), the E_i can be used in MCDA or optimisation algorithms, representing the domestic energy deprivation levels. In these algorithms, the objective should be to minimising the E_i in trade-off with other criteria to find the best option or optimal solution.

The above steps define the two-dimension PFPI, estimating the potential fuel poverty that could arise as a result of future building energy interventions. The whole process of the PFPI is illustrated in Fig. 1.

3.2. Case study

A pilot appraisal of an energy intervention is carried out to demonstrate the application of the proposed approach. The study uses the Liverpool John Moores University (LJMU) Exemplar Houses as the case study to represent the real environment [86]. In partnership with the Building Research Establishment (BRE), the LJMU has built three houses in Liverpool, UK, compliant with the standards of the 1930s, 1970s and 2010s to test and develop new green technologies and building methods in the different housing generations [86]. These houses represent three different generations of three-bedroom terraced dwellings with their specific design and construction norms. The houses' picture, layout and simulated model can be found in Appendix A. The houses are similar in terms of size, location, and exterior design, but they differ in buildings' envelope and slightly in interior layout and design. Fig. 2 illustrates the main differences of the building typologies in the walls and flooring (further details on buildings' envelopes are given in Appendix A).

The three houses are pre-equipped with individual gas-fired boilers to heat the building space using water radiators and also to provide domestic hot water. In a renovation scenario, Air-Source Heat Pumps (ASHP) are considered to replace the existing heating devices, in line

Table 3
Monetary poverty thresholds for household typologies based on the equivalised disposable income per household (£ per year) by government region, UK.

UK region	Households with at least one person aged 65 years or over (£/year)		Households with at least one person with a disability (£/year)		Households in rural areas (£/year)		Other households (£/year)	
	PT	*SPT*	*PT*	*SPT*	*PT*	*SPT*	*PT*	*SPT*
North East	15,391	10,260	14,620	9746	15,778	10,518	16,055	10,703
North West	13,571	9048	14,114	9409	18,808	12,538	15,805	10,536
Yorkshire and The Humber	14,043	9362	14,676	9784	17,057	11,371	16,032	10,688
East Midlands	14,543	9696	16,009	10,673	18,164	12,109	16,636	11,090
West Midlands	14,880	9920	14,682	9788	19,449	12,966	16,015	10,677
East	14,880	9920	14,682	9788	19,449	12,966	19,834	13,222
London	16,798	11,198	17,164	11,443	NA	NA	20,956	13,970
South East	16,562	11,042	17,785	11,856	20,820	13,880	19,588	13,058
South West	16,612	11,075	16,922	11,281	18,260	12,174	17,764	11,842
Wales	14,269	9513	14,423	9615	15,818	10,546	15,863	10,576
Scotland	14,708	9806	14,903	9935	16,760	11,174	16,351	10,901
Northern Ireland	14,345	9564	14,323	9548	NA	NA	15,146	10,097

Table 5
Energy cost thresholds (ECTs) for household typologies based on the equivalised fuel cost (£ per year) by government region, UK.

UK Region	*ECT* for households with at least one person aged 65 years or over (£/year)	*ECT* for households with at least one person with a disability (£/year)	*ECT* for households in rural areas (£/year)	*ECT* for other households (£/year)
North East	898	970	962	1015
North West	1035	1020	914	1024
Yorkshire and The Humber	972	1021	888	1002
East Midlands	913	939	929	982
West Midlands	1055	1078	1130	1053
East	1047	1047	1044	1059
London	1048	1031	NA	992
South East	1023	1043	1092	1006
South West	955	1005	928	992
Wales	898	859	542	915
Scotland	973	1056	1050	1056
Northern Ireland	962	971	NA	1046

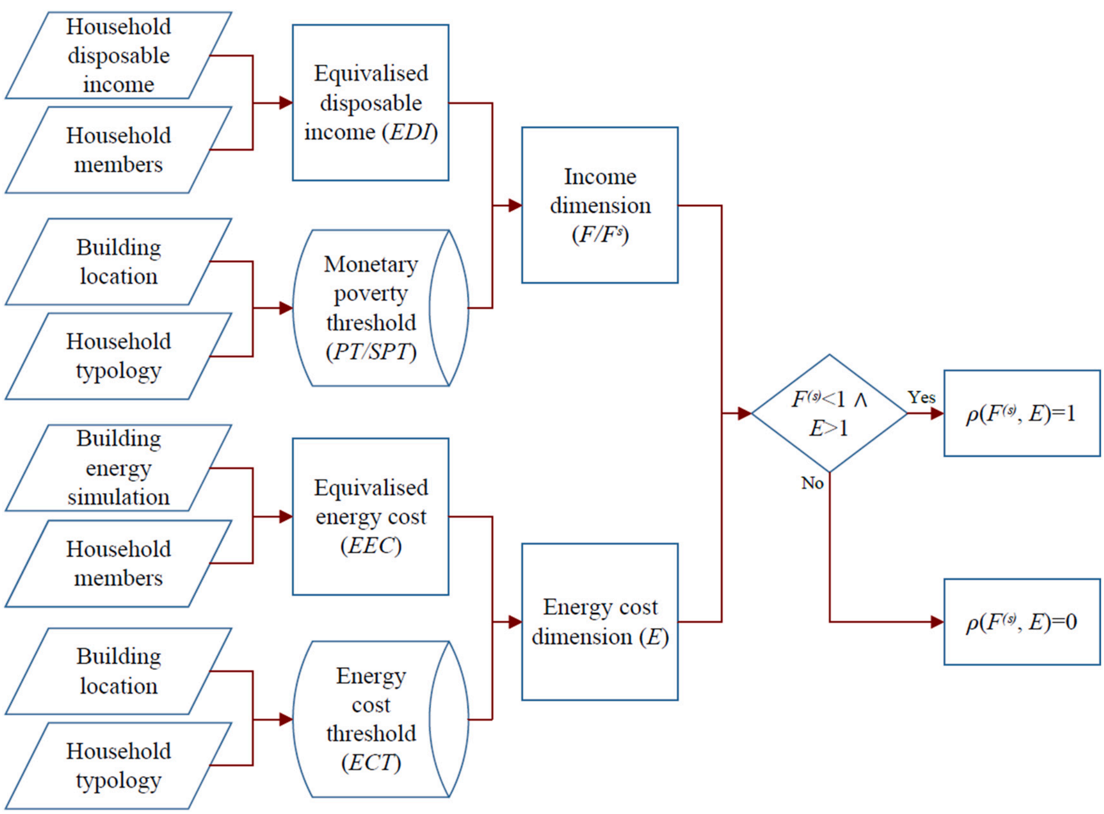


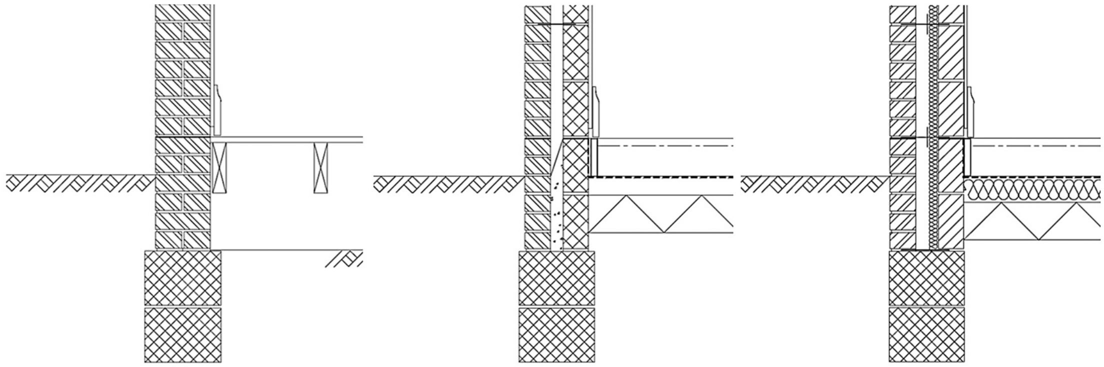
Fig. 1. The PFPI calculation flow diagram.

with the UK's decarbonisation strategies [9]. The UK Government has reaffirmed in the Heat and Buildings Strategy that they target to surge the domestic heat pump installations from 33,000 in 2019 to 600,000 units per year by 2028 [9]. ASHPs are a crucial technology for delivering this target and have already proven their life-cycle economic justification in various new and existing homes [87,88]. For the heat pump installation in the case studies, the existing hot water pipework and water radiators will be used to distribute the heat throughout the house (air-to-water heat pump configuration). No changes in the existing heating circulation system or thermal improvements in the buildings have been considered to minimise the costs and installation work. Table 6 shows the specifications of the current heating system in the buildings and their low-carbon alternative.

Switching from gas to electricity for heating using heat pumps could run the risk of an increase in energy bills without well-considered planning and design, due to the cost differential between electricity and gas (today, electricity costs about five times the price of gas per kWh for British end-users). This is notified in numerous reports and articles [87,89,90], many of which have warned that heat pump implementation in poorly insulated homes would deepen the fuel poverty status in the vulnerable population [62]. Thus, installing heat pumps in the case studies needs to be investigated beforehand to reduce the potential risks.

4. Results and discussion

The results obtained from the analysis of the intervention scenario are discussed in this section. Following the case study, the utility of the proposed method is appraised, and its potential contributions are underlined.



(a) Wall: 215mm thick solid masonry wall (two bricks wide)
Floor: 22mm floorboards and 200mm joists on well-compacted MOT1

(b) Wall: 102mm outer face brick, 50mm clear cavity, 100mm lightweight block, and 13m plaster skim to inner face
Floor: 175mm concrete slab and 75mm sand blinding on well-compacted MOT1

(c) Wall: 102mm outer face brick, 50mm clear cavity, 40mm insulation board, 100mm medium-density block, and 13mm Gyproc wallboard
Floor: 175mm concrete slab and 100mm rigid insulation on well-compacted MOT1

Fig. 2. Schematic drawing and characteristics of the walls and flooring in the **a)** 1930s, **b)** 1970s, and **c)** 2010s building typologies.

Table 6
Configuration of the heating systems, the current gas boiler and the alternative heat pump.

Heating source	Existing gas boiler	ASHP
Space heating system	Central heating via water radiators	Central air-to-water system via radiators
Heating capacity (kW)	21	8
Seasonal efficiency	0.91	3.10
Heating SCoP	0.81	2.77
DHW delivery efficiency	0.95	0.95
Storage volume (L)	–	300
Space heating setpoint (°C)	20.0	20.0
Hot water supply setpoint (°C)	60.0	60.0

4.1. Simulation results

Results obtained from the simulation have been used to analyse the application of the same intervention scenario to three representative terraced houses. For this analysis, the same family of three members comprising a couple, both aged under 65 and employed, and a child aged over 14, is assumed to live in each house to make the results comparable. The case studies are modelled in the IES-Virtual Environment and calibrated with field measurements to make them valid for simulating the renovation scenarios. Energy costs are calculated based on the 2020 average domestic gas and electricity unit rates in the UK regions, reported by BEIS [91,92]. Regarding the carbon emissions, UK government GHG conversion factors are used, taking into account all the direct and indirect carbon emissions that occur in the system's value chain [93]. Table 7 summarises the key values used for the simulation.

Table 7
Key inputs for cost and carbon simulation.

Simulation factors	Value	Description
Electricity unit price (£/kWh)	19.39	From Table 2.2.3 in [91] for Northwest England
Gas unit price (£/kWh)	4.06	From Table 2.3.3 in [92] for Northwest England
Electricity emission factor (kgCO2e)	0.288	Scope 1 to 3 emissions including transmission and distribution (T&D) emissions and well to tank (WTT) emissions for both T&D and generation [93]
Gas emission factor (kgCO2e)	0.208	Scope 1 to 3 emissions including WTT emissions [93]

Further parameters of modelling and assumptions regarding the building physics, weather conditions, and occupancy are presented in Table A.1 in Appendices. The houses' energy consumption and operational cost and carbon emissions for supplying heat, hot water, and electricity, before and after implementing the intervention are calculated, as shown in Table 8. The results from modelling the present status are validated with the houses' actual energy use, acknowledging the models' accuracy and reliability for simulation of future scenarios. It should be emphasised that this study has only focused on analysing the operational energy, cost, and emissions. However, more parameters such as upfront costs and embodied carbon emissions need to be considered to make a holistic comparison between the various solutions in terms of their life cycle impacts.

The outcomes of the energy simulation show that in general, the heat pumps considerably reduce the total primary energy demand in all building types. Despite the electricity demand which is almost doubled in the modern house and more than tripled in the 1930s house, the gas usage is zeroed out in every case study when they are equipped with the ASHP. Therefore, the increased reliance on electricity is more than offset by the elimination of gas from the buildings' energy system. As seen in the results, the lowest annual saving is achieved in the 2010's case with a 57 % reduction in the annual primary energy consumption, whereas the reduction rate is 62 % in the oldest case study. Bearing in mind that heat pump installation might require some building upgrades such as rewiring, insulation, and improving electricity network connection, it is assumed that no upgrades are needed in the case studies. Furthermore, the mass uptake of heat pumps places a burden on the electricity grid which needs to be addressed to maintain a secure and resilient power supply [87].

Moving forward to the environmental performance, heat pumps could decrease the burden on the environment, as a considerable reduction in operational carbon emissions is achieved by them in all cases. This saving is significant in all the case studies, ranging between 45 and 49 %, and it could be further enhanced by increasing the share of renewable electricity in the grid. However, by increasing the uptake of the whole life carbon approach which takes the embodied carbon and refrigerant impact into account, the environmental advantages of heat pumps should be reconsidered, not limited only to the operational carbon emissions [94].

Unlike the direct carbon emission, economic factors are found to be highly dependent on building typology and energy tariffs. In the house built on the 2010 building regulations, where double glazing, well-

Table 8
Simulation results for annual energy performance of the buildings.

Results	1930s house		1970s house		2010s house	
	Gas boiler	*ASHP*	*Gas boiler*	*ASHP*	*Gas boiler*	*ASHP*
Electricity demand (MWh)	2.81	8.90	2.81	7.32	2.81	5.49
Gas demand (MWh)	20.43	0.00	15.03	0.00	10.11	0.00
Total building energy (MWh)	23.24	8.90	17.84	7.32	12.93	5.49
Total operational carbon emissions (kgCO_2e)	5061	2565	3937	2109	2915	1580
Total operational energy cost (£)	1405.5	1603.3	1167.8	1317.9	951.5	988.1

insulated envelope and balanced airtightness are implemented, the total energy bill composed of both gas and electricity costs has slightly increased (3.8 %). This argues that ASHPs could cost more than gas boilers to run even in newly built buildings due to the current cost differential between electricity and gas. Modifications of the energy tariffs and putting supportive financing schemes into practice would increase the heat pumps' competitiveness in the market. On the other side, £198 (14 %) is added to the running energy cost of the family living in the 1930s house. Regardless of the upfront cost, which is not assessed in this study, the increase in operating cost could appear as a financial burden, making ASHPs less favourable for inefficient and poorly insulated homes. The comparative analysis is illustrated in Fig. 3 where variations of the energy, economic and environmental factors after implementing the intervention measure compared to the current scenario are presented.

The conducted comparative analysis presents a complex decision-making problem as the investigated factors do not converge toward a single best scenario. In this study, the ASHP with an efficiency of 3.1 is advantageous over the gas-fuelled boiler in terms of energy and environmental footprint but could not economically be served as a profitable option for households at today's energy tariff rates in the UK. Switching to heat pumps in 1930s house is more beneficial as they could serve a large amount of saving in primary energy use and carbon emissions. On the economic side, however, ASHPs can be favoured in new homes as they economically perform better in well-insulated properties and lead to much lower increases in energy bills. It means that energy and carbon reductions of the heat pump replacements do not necessarily have a linear relationship with their economic attractiveness. Similar conflicts between environmental indicators of sustainability and cost factors have already been observed in some research projects [95]. Fuel poverty is another factor that should be considered at this stage of the decision-making as it is analysed in the following section.

4.2. Fuel poverty investigation

The developed method for evaluating fuel poverty under the interventions is applied to investigate the case studies. To do so, the

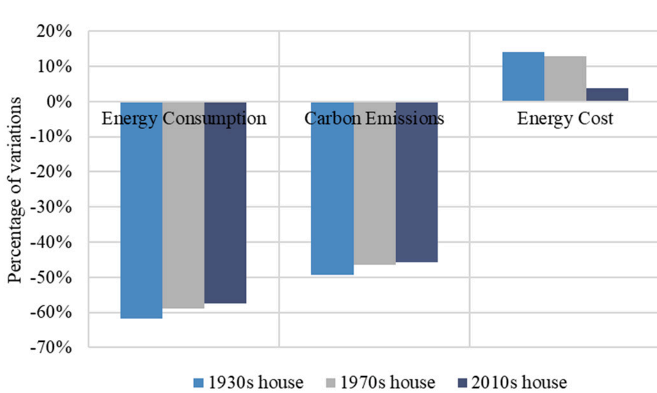


Fig. 3. Variations of the energy, economic and environmental factors in the representative houses equipped with ASHPs compared to the basic gas-fuelled system.

income dimension of the PFPI is firstly analysed for the same assumed family living in three case studies. Assuming a total disposable income of £21 k/year for the considered household (family of two adults and a child aged +14), the value of equivalised disposable income (*EDI*) to be used in the PFPI method equals £14,789/year. The *EDI* is achieved by dividing the disposable income by the relevant equivalisation factor from Table 2 which is 1.42 (=0.58 + 0.42 + 0.42) in this case. Locating in Liverpool in North West England, the *PT* and *SPT* for the family living in the three case studies are £15,805 and £10,536 per year, respectively (Table 3). Accordingly, the values of F_i and F_i^s are obtained to be 0.94 and 1.40, using the Eqs. (3) and (4), indicating that in terms of the economic dimension only, the assumed family is prone to be in fuel poverty but secure from severe fuel poverty.

Following that, the energy cost dimensions of the PFPI are calculated and given in Table 9. Estimated energy costs (given in Table 8) are divided by the equivalisation factor of 1.07 (given in Table 4), corresponding to the assumed family, to obtain the equivalised energy cost (*EEC*). The *EEC*s for the 1930s and 1970s houses, both in current and future scenarios, are more than the corresponding thresholds *ECT*s. Therefore, the E_i values for these houses, obtained according to Eq. (5), are greater than one, indicating that with regards to the energy costs only, dwellers of these houses are exposed to fuel poverty. The fuel poverty gap is also presented in Table 9 which is the required reduction in energy bills to no longer be fuel poor [96]. This equals the difference between the household energy costs and the energy cost threshold ($Fuel\ poverty\ gap = EEC_i - ECT_{t(i)}$), representing the depth of fuel poverty [83]. The fuel poverty gap is not applicable for the 2010s house (*NA* in Table 9) as the household energy cost does not exceed the energy cost threshold.

By gathering F_i and E_i elements into the PFPI indicator, it can be derived that $\rho(F_{1930s\&1970s}, E_{1930s\&1970s}) = 1$ and $\rho(F_{2010s}, E_{2010s}) = 0$, indicating that ASHP installation will exacerbate fuel poverty in the 1930s and 1970s households. Even efficient electric heating technologies such as ASHPs are likely to increase the energy bills and grow the intensity and prevalence of fuel poverty. This risk could easily counteract the potential energy and environmental benefits of the heat pumps. Therefore, such interventions in the old houses may not be recognised as a suitable option, unless the energy and environmental factors are considered to be much more important than the operating cost and fuel poverty issue. It is also noticeable that the $\rho(F^s_{1930s\&1970s\&2010s}, E_{1930s\&1970s\&2010s}) = 0$, indicates that the assumed family will not experience severe fuel poverty in any of the building

Table 9
Energy cost parameters of the PFPI for the case studies.

Results	1930s house		1970s house		2010s house	
	Gas boiler	*ASHP*	*Gas boiler*	*ASHP*	*Gas boiler*	*ASHP*
EEC (£/year)	1313.5	1498.4	1091.4	1231.7	889.2	923.4
ECT (£/year)	1024	1024	1024	1024	1024	1024
E	1.28	1.46	1.06	1.20	0.86	0.90
Fuel poverty gap	289.5	474.4	67.4	207.7	NA	NA

models.

What stands out in Table 9 is that the E_i factor in the PFPI closely correlates with the fuel poverty gap, making it an applicable indicator to get a sense of the depth of fuel poverty. Accordingly, options with less value of E_i should be favoured in decision-making or analyses. It can be seen that properties with higher ages correlate with higher energy demand and higher E_i factor, resulting in a larger fuel poverty gap. The findings are consistent with the national figures; the 2022 annual fuel poverty report in England (based on the 2020 data), Fig. 4, shows that the trend generally correlates to the decreasing fuel poverty gap in more recently built buildings as energy efficiency broadly improves with decreasing property age [97]. Furthermore, Table 9 suggests that the installation of ASHPs in older dwellings could further increase the energy costs, and consequently, the fuel poverty gap. These results corroborate the findings of a great deal of the previous work on heat pumps [87,98], confirming that this technology performs more efficiently and affordably in well-insulated buildings with lower energy demands.

This investigation contributes to the general understanding of the performance of the ASHP installation in various housing generations. The findings suggest that revenues of the ASHP interventions could be seriously undermined if they are not accompanied by sufficient energy conservation measures and modification of the energy prices, as they can result in increasing the likelihood and depth of fuel poverty. This can acknowledge the concern expressed by the major stakeholders in the UK over the readiness of the building stock for the widespread roll-out of heat pumps [87,98]. To address this concern, the UK government has already committed to energy-efficiency improvement targets in the building stock like the ambition to upgrade as many homes as possible to EPC band C by 2035, as set out in the Clean Growth Strategy [99]. Alongside these improvements, electricity and gas price adjustment and other financial incentives are essential to increase the uptake of green choices. Despite being ambitious and relatively timely in setting the targets and standards of fabric upgrades in buildings, the UK government has not been clear with regard to the actions required to address market distortions. By systematically reducing the cost and emissions of electricity generation, as well as improving the buildings' energy efficiency, heat pumps could become the economically and environmentally preferable technology in almost all cases.

4.3. Contribution of the proposed approach

As pointed out earlier, fuel poverty indicators and measurement methods have commonly been criticised for not being sensitive to all influencing factors, leading to inadequate understanding of the issue and non-inclusive identification of vulnerable households. As a result,

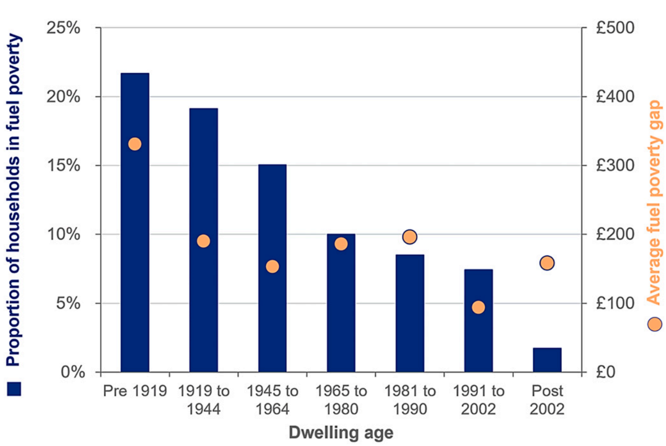


Fig. 4. The proportion of the households in fuel poverty and average fuel poverty gap by property age, England, 2022 [97].

people living in fuel poverty have been under-represented in some intervention projects and have faced worsened social inequalities after implementing the interventions [10,11]. Reflections of these limitations can also be found in some policy decisions, where they cannot prioritise low-income families and consequently fail to support them through the right measures [100].

The proposed method in this research, however, lays the grounding for encapsulating fuel poverty at the nexus of technological innovations and socio-economic evaluations. Using the PFPI, fuel poverty can be included in the early stages of selecting or sketching interventions as a design/decision factor in conjunction with other economic, environmental, and technical factors. Furthermore, the developed PFPI is a two-dimensional index to predict the likelihood of fuel poverty under future interventions. Most of the existing objective indicators of fuel poverty assess the current status of fuel poverty primarily based upon the households' income and energy expenditure and comparing them with the national-level thresholds. There are two major drawbacks associated with these indicators that are attempted to be addressed by the proposed method.

The first one is the concern with setting the thresholds and under-representation of the socio-spatial vulnerabilities in the national-scale comparisons [101]. It is recognised that some socio-spatial considerations, namely particular geographical requirements or those associated with disability and illness, older population, lone parents, and young children, can be better reflected at sub-national scales [66]. Poverty and energy cost thresholds can be set in a more targeted manner by categorising the community based on socio-spatial characterisation. Therefore, these thresholds in the present research are set at the regional scale, broken down into four household typologies.

The second highlighted drawback is that income/expenditure-based indicators usually cannot differentiate between actual and required energy costs. Therefore, one of their common pitfalls is the failure to reflect the underconsumption of energy services in poor monetary situations or the overconsumption of households with special requirements [66,102]. To address this, individual simulations of the household's energy demand can be used instead of actual energy use. Simulated energy demand and its associated costs can be obtained from sophisticated energy simulation tools. The inherent quality of using energy simulations could bring some advantages to the investigations as follows:

- Measuring fuel poverty based on the modelled energy expenditure could avoid underestimation of the risk of fuel poverty (false negative) that may arise due to the poor energy performance of the buildings or inadequate use of energy services. Many fuel-poor households self-ration their energy consumption or even self-disconnect the energy services in serious instances of vulnerability [103]. Using energy demand, households who restrict their energy use below comfort levels due to a lack of monetary resources, known as hidden energy poverty (HEP), can be identified [44,80].
- Today's energy simulation tools can take multiple factors into calculations to produce accurate and reliable predictions. The impact of a wide range of factors on the building energy performance, such as thermal and physical characteristics of dwelling components, the efficiency of heating systems, ventilation rates, household characteristics, and home appliances, are usually taken into account in these simulations [70].
- Household characteristic is a crucial element of fuel poverty that is not often represented in the common measurement methods. Incorporating household-driven parameters along with building-physics calculations in the software tools can make a more realistic basis for fuel poverty assessments. Multiple household-related parameters such as demographic characterisation, level of activity, energy use pattern, and comfort conditions can be taken into account in simulations. For instance, the comfort temperature of elderly and infirm

households can be set to 23 °C, whereas 21 °C is often considered sufficient for most of the other occupants [104].

- This method also offers an important advantage of accounting for geographical specifics and local parameters like local energy tariffs and climatic conditions. Therefore, the proposed indicator can provide a more realistic estimate of energy demand and expenditure, which could lead to a more meaningful prediction of fuel poverty status.
- This method significantly reduces the time and effort required for data collection and facilitates the studies on larger scales, avoiding the need for complexities of post-occupancy building assessments and household surveys.

Having said that, some constraints can be expressed using the developed method, mostly due to potential flaws in the simulation of the building energy behaviour and less reliability compared to monitored data [105]. It is typically challenging to accurately define all the details of occupancy behaviour and activities in the simulations, due to the behavioural complexity and diversity of the occupants [106]. In addition, modelled energy expenditure in studies is often higher than the real spending data. This could cause an overestimation of the risk of fuel poverty for households who do not have low incomes and high costs (false positive) [63,66].

5. Conclusions

The energy interventions in the building sector could have significant benefits for climate stability and sustainable development, but also hold the risk of degrading the living standards of the vulnerable population if they are not built on a solid understanding of the dynamics between buildings, energy systems, households and the community. Hence, it is increasingly attempted in the interventions to consider social factors, aiming for delivering a just transition toward low-carbon buildings. This constitutes a decision-making challenge in which multiple and sometimes conflicting objectives need to be pursued to successfully identify the best possible solutions. While multi-criteria analysis methods have enormously facilitated the study of these factors in an integrative way, social factors are less investigated in the design and decision-making stages. This has caused many low-income families to be underrepresented in policies, sometimes worsening the social inequalities they face. In this respect, it is argued that fuel poverty is one of the most important social factors which needs to be observed at the primary stages of energy interventions in the domestic sector. Implementing low-carbon measures without considering their impacts on fuel poverty could potentially expose more households to the risk of energy deprivation. Therefore, the importance of utilising predictive approaches which allow fuel poverty to be incorporated into design and decision-making processes is highlighted in this study.

Following that, a novel predictive indicator, the PFPI, is developed in this study that can provide a vision of the potential impacts of the interventions on fuel poverty at the early stages of the projects. The PFPI is composed of two dimensions, households' income and required energy expenditure, which minimise the need for complex building assessment tools, robust databases, and household surveys. Using the developed method, decision makers will be able to uncover the linkage between building energy interventions and fuel poverty in a simple way, assisting them in designing more targeted energy interventions. The PFPI can also be incorporated into MCDA and SA frameworks, allowing the trade-offs between fuel poverty and other decision criteria through a unified multi-criteria analysis. The proposed approach gives precedence to fuel poverty, bringing it forward from the post-intervention to the design and policy-making phase.

For applying the proposed method, a new classification of household typologies based on their location and the composition of the dwellers is presented in this study to reflect the occupants' behavioural variations. This allows for defining more precise thresholds for financial and energy vulnerability and consequently, improving the adopted MEPI and LIHC indicators. For the UK context, the required thresholds, *PT*, *SPT*, and *ECT*, are calculated based on the 2020 data and could be used as a reference for future fuel poverty assessments in the UK. To adopt the PFPI for other countries, these parameters must be calculated based on the available data and breakdowns should be redefined to suit their specific requirements. Furthermore, equivalisation of income and costs are applied to reflect the households' size and demographic profile in assessments. This allows making comparisons between disparate income levels and energy demand based on a common unit (the person-equivalent).

It is important to highlight that the new method may not be able to precisely predict the probability and depth of fuel poverty, especially for unknown future occupants. This is due to several uncertainties and unpredictable factors, such as households' individual behavioural and psychological mechanisms, which cannot be modelled using computer models, making fuel poverty a complex social issue that stretches far beyond a simple model of cause and effect. Such nuances of fuel poverty could be possibly captured only through in-depth surveys and prolonged interactions with households. However, the new predictive index could shed light on possible fuel poverty challenges that future building interventions could impose, enabling the move from a remedial to a preventive approach. Also, it enables exploring synergies and trade-offs between fuel poverty and a range of criteria that aids in choosing the most sustainable measures.

From a broader perspective, this study suggests that some social implications of the low-carbon transition measures can be addressed through predictive models. Focusing on fuel poverty in this paper, the authors hope the new approach will contribute to the scholarship in the field by paving the way for fuel poverty to be assessed at the design and planning stages. This forms the basis for further research and practice to investigate the effectiveness of such methods, by checking the predictive models against the field data from real-life projects. Additionally, the model can facilitate future research on investigating the synergies and tensions between building interventions and different market mechanisms and incentives. In a broader sense, more research is needed to devise predictive models for quantifying the social implications of low-carbon transitions, tackling these issues before they arise.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All the used data and datasets are referenced in the references section.

Acknowledgements

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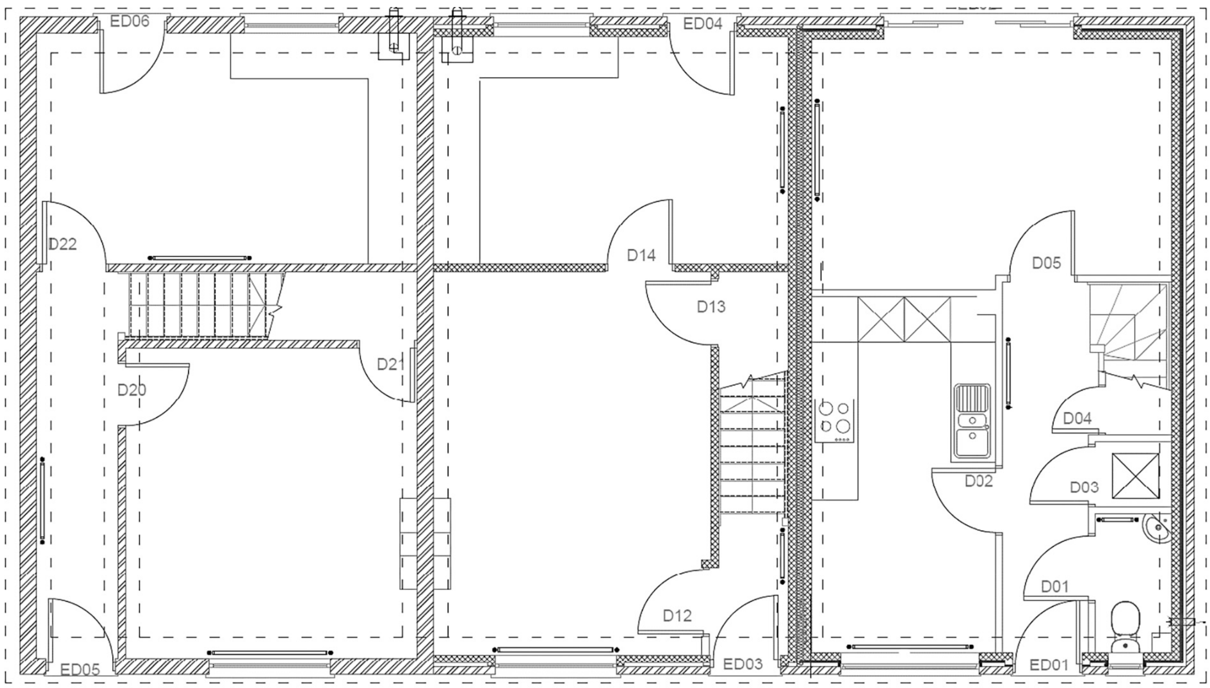
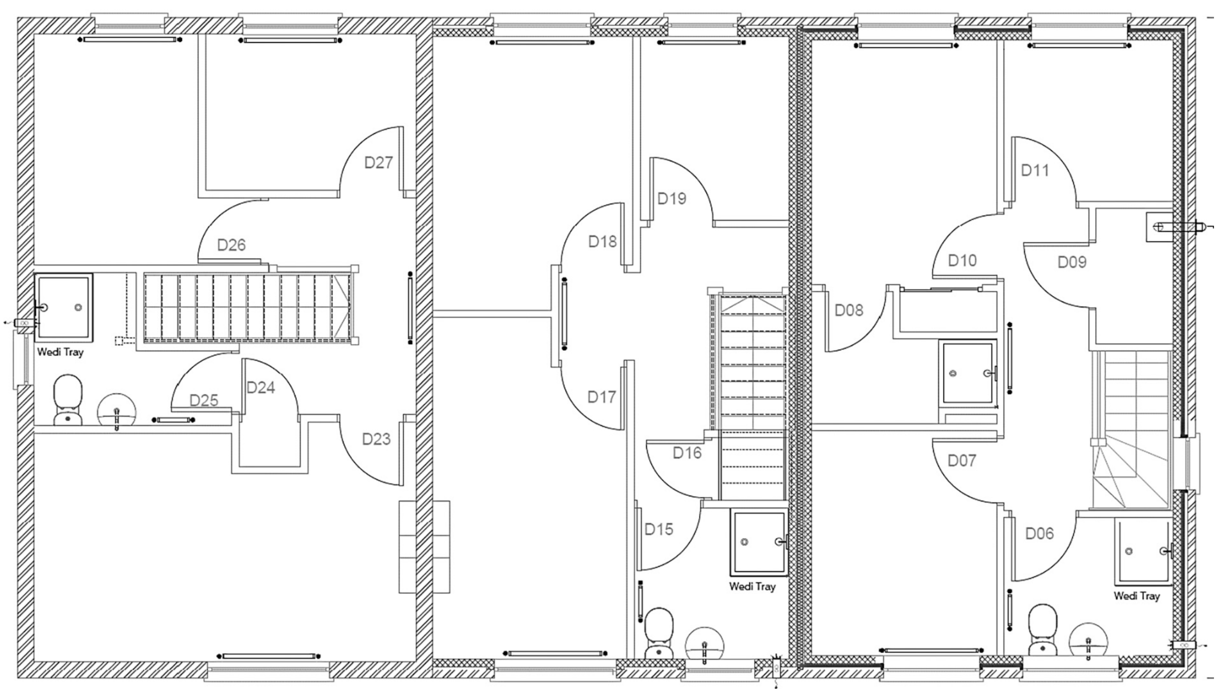
Appendix A. Case study data and figures

Fig. A.1. Case study, the LJMU Exemplar houses.

Fig. A.2. Case study model in IES-Virtual Environment.



(a)



(b)

Fig. A.3. Layout of the case studies, 1930s house on the left, 1970s house in middle and 2010s house on the right; **a)** Ground floor, **b)** First floor.

Table A.1
Modelling parameters and assumptions.

Modelling parameters	1930s house	1970s house	2010s house
Building parameters			
Exterior wall U-value (W/m^{2}K)	1.65	0.63	0.26
Roof U-value (W/m^{2}K)	1.46	0.76	0.17
Floor U-value (W/m^{2}K)	0.99	0.83	0.18
Glazing U-value (W/m^{2}K)	4.12	2.11	1.54
Ventilation max rate (ACH)	1	1	1
Infiltration max flow (ACH)	0.95	0.55	0.25
General model settings			
Available living area (m^2)	88.4		
Building conditioned volume (m3)	373.5		
Number of occupants	3 (2 adults and 1 child aged +14)		
Hot water demand (L/day)	150		
Internal gain sources	Occupants and electric appliances		
Max sensible heat gain (W/person)	50		
Design weather			
Weather station	Liverpool Airport		
Weather data source	ASHRAE design weather database v6.0		
Max dry-bulb temperature (°C)	28.1		
Min dry-bulb temperature (°C)	8.5		
Winter design temperature (°C)	−2.2		
Max humidity (%)	100.0		
Min Humidity (%)	29.0		
Mean humidity (%)	82.3		

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