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The validity of the index of vulnerable homes: evidence from consumers vulnerable to energy poverty in the UK

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ABSTRACT

Energy poverty is a multidimensional issue, and this means that it is difficult to understand the different levels of vulnerability to this phenomenon and its relationship with households' quality of life. This paper presents the validation of an innovative index for the analysis of vulnerability to energy poverty according to monetary, energy, and thermal comfort factors: The Index of Vulnerable Homes (IVH). The IVH goes beyond the use of single self-reported indicators of thermal comfort, and instead uses the adaptive thermal-comfort model defined in the normative UNE EN 15251:2007 to assess thermal comfort in relation to energy poverty. Furthermore, it has the potential to evaluate the societal impacts of current energy poverty policies by providing the economic analysis of different situations of vulnerability. The IVH is validated by comparing its results to those obtained from a survey conducted in a small-scale study undertaken in Salford, UK. To this end, evidence from households living in terraced houses built before 1980 is used to analyze health status in terms of vulnerability to energy poverty vulnerability according to their monetary situation and the characteristics of the dwelling. In the end, the results show good agreement between both the IVH's assessment and households' evidence, leading to consider the IVH as a suitable approach to understanding different levels of vulnerability to energy poverty.

KEYWORDS

Energy poverty; energy efficiency; health; vulnerable consumers; healthcare

1. Introduction

Energy poverty (EP), understood as the inability of a household to achieve a socially and materially sufficient level of domestic energy service (Bouzarovski and Petrova 2015), is a worldwide issue that has risen up the agenda for governments and policymakers. At an EU level, the Third Energy Package to clean Energy for all Europeans (Directorate-General for Energy (European Commission) 2019) obliges Member States to acknowledge the prevalence of EP in their Energy Climate Plans. To help Member States address the issue, the EU Energy Poverty Observatory, an initiative financed by the European Commission, provides four primary indicators for the analysis of EP: inability to keep home adequately warm, arrears on utility bills, high share of energy expenditure in income, and low share of energy expenditure in income (European Commission 2018b). However, due in part to the multidimensional aspect of EP, the effectiveness of current EP indicators is limited, and it is therefore necessary to combine various indicators and to analyze their results together (Castaño-Rosa et al. 2019b).

Additionally, even though EP has traditionally been associated with countries experiencing cold winters, climate change has increased current temperatures and brought associated health impacts, resulting in summertime EP also having a high public impact (Sanchez-Guevara et al. 2019; Thomson et al. 2019).

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In this context, it is known that many people living in energy inefficient properties with low income struggle to meet their energy needs for heating and cooling, and they have an associated risk of cold- and heat-related illness. Although the relationship amongst health, fuel poverty, cold homes, and overheating risk has been analyzed in a large number of studies (ASSIST 2GETHER 2018; Baker et al. 2016), it remains difficult to identify the direct impact of this relationship due to the multi-dimensional aspect of EP. This paper presents a validation of the Index of Vulnerable Homes (IVH) by comparing its results to those obtained from a small-scale study undertaken in Salford, where energy-efficiency interventions were carried out. Additionally, it adds to other evidence (Castaño-Rosa 2018; Castaño-Rosa, Solís-Guzmán, and Marrero 2018, 2020) that the lack of feasible measures – which would help the understanding of different situations of vulnerability to EP (Castaño-Rosa et al. 2019b) – leads the IVH being a comprehensive measure to better understand EP vulnerability at the local-scale (Castaño-Rosa et al. 2019a) and, consequently, to be validated in this work. To this end, a literature review of the multiple social vulnerabilities that influence EP, highlighting the complexities of targeting vulnerable households and the need to better understand EP, is included here. A survey, based on the required data for the IVH's application (monetary situation, health status of householders and characteristics of dwelling) and gathering different energy vulnerability factors such as access, affordability, flexibility, energy efficiency, needs, and habits, was defined to obtain the information needed for this work (householders and dwellings characteristics). In the end, a comparative analysis between the assessment of households' health status estimated by the IVH and the reported in the survey is carried out.

2. Literature review

EP is a multidimensional issue shaped by a range of factors that includes access, affordability, flexibility, energy efficiency, needs, and habits (Bouzarovski, Petrova, and Tirado-Herrero 2014; Simcock and Petrova 2017).

In terms of access, appropriate domestic energy infrastructures are closely related to the inability of households to access to minimum energy services, as well as the possibility of moving toward a more affordable option or to switch the type of fuel and supply (Robinson, Lindley, and Bouzarovski 2019). Additionally, Middlemiss et al. (2019) show the relationship between households' social relations and EP as a key factor in the ability of a household to access to energy services, suggesting the potential impact of considering the relationship amongst access to energy services, social relations (including good connection with relatives, feeling of shame because of its social position), and social conditions (by means, for example, of health status, monetary resources, fuel/energy prices) and positions (including tenure and employment status, role in the family).

Affordability is not experienced equally by different household types; factors including household size, gender, employment status, labor information, location and characteristics of dwelling lead to different situations of EP and, as a result, a good understanding of how different social and energy vulnerability factors can lead to different situations of EP would help to adopt effective policy measures (Aristondo and Onaindia 2018b; Meyer et al. 2018). Similarly, Scarpellini et al. (2019) argue that there is a need to analyze the relationship between geographical factors and EP in order to better understand the economic-impact of specific supports provided by both private and public institutions. In this sense, a reduction in households' food expenditure, and therefore calorific intake and quality of diet can be observed amongst low-income families, specifically during colder periods when they may have to make the difficult decision of whether to spend household budget on heating or on food (Anderson and White 2019; Beatty, Blow, and Crossley 2011).

When considering flexibility, the stability of household income, energy costs, characteristics of dwelling, tenure status, health problems, and emotional engagements are key factors in the autonomy and flexibility of households (Longhurst and Hargreaves 2019; Middlemiss and Gillard 2015). Additionally, most vulnerable people (such as elderly, teenagers, or disable people) need to be considered when determining social assistance. A lack of information about available financial support, making it difficult to access additional financial benefits, is known as one of the main causes of the household's inability to switch energy supplier or conduct retrofit (Sanz-Hernández 2019). In this sense, social workers have been playing a key role in the detection of EP; they act as mediators and make contact with vulnerable households daily, and are therefore able to detect a situation of EP (Scarpellini et al. 2017). On the other hand, many households, due to the lack of monetary resources, do not have the ability to retrofit their houses (Boemi and Papadopoulos 2019), suggesting that the provision of financial benefits for the most vulnerable households who cannot afford different energy-efficiency interventions may be beneficial, improving households' empowerment and flexibility to address EP.

Low levels of maintenance and inadequate characteristics of dwelling lead to disproportionally high energy consumption – due to low energy efficiency – as well as affecting the health of households. The benefits that energy-efficiency interventions have on households' quality of life are well established (Boemi and Papadopoulos 2019; Ortiz, Casquero-Modrego, and Salom 2019). Many studies have shown the impact of cold and damp housing conditions on both morbidity and excess winter mortality (Aristondo and Onaindia 2018a; Rudge 2011; Thomson and Bouzarovski 2018). A 25% higher risk of dying is associated with households living in the coldest homes during the winter (Hamilton et al. 2017; Oliveira et al. 2017). Furthermore, poor indoor maintenance is also related to health problems, specifically the 30–50% increase in respiratory problems associated with damp homes with mold (Fisk, Lei-Gomez, and Mendell 2007; Oliveira et al. 2017). Intervention studies, often following a heating intervention, have found a relationship between living in a damp house with mold and allergic symptoms, asthma, and respiratory tract infections (Gibney, Ward, and Shannon 2018; Liddell et al. 2016; Zhang et al. 2019). At the same time, living in poor quality dwellings with cold temperatures increases the possibility of systolic and diastolic blood pressure (a rise of blood pressure is come from a narrow of blood vessels) (Bai et al. 2018; Ponjoan et al. 2017), as well as the risk of thrombosis that leads to heart attacks and strokes (Tammes et al. 2018). In addition, dampness and mold have been associated with stressful situations in reference to not being able to keep a clean home without the smell of damp and concern for family members' health (Grey, Jiang, and Poortinga 2015; Spirkova et al. 2016).

Many households that are vulnerable to EP need of special attention (for example, different energy requirements, support from assistance schemes, additional energy requirements for health reasons) when defining effective measures. In this sense, energy support services (including home visit) can be essential for vulnerable groups (Baker et al. 2019). With regard to vulnerable groups, an increase in hospital admissions for respiratory conditions in older people (aged over 65) during the winter has been observed (Ponjoan et al. 2017). Furthermore, the risk of death by a respiratory infection can increase if a person suffering from a chronic respiratory illness sleeps in a cold bedroom, mainly due to the immune system and resistance to infection being weakened by the cold air that affects the bronchial lining of the respiratory tract (Mason and Roys 2011; Pierse et al. 2013).

Habits and behaviors of householders should also be considered. EP measures have traditionally been based on the use of objective indicators (such as income level and energy consumption of households, energy-efficiency of dwellings) and subjective measures based on perception. However, people's behavior – covering use of the home, household structure and dynamics, finance of the households, social activity and relations, and heating arrangements and thermal comfort – have recently been explored (Kearns, Whitley, and Curl 2019). Feeling comfortable at home, feeling confident to invite friends to visit, an increase in the size of the liveable space within which day-to-day activities can take place, as well as being less concerned or anxious about energy consumption bills, are related to this factor and can lead to increase the risk of social exclusion. Similarly, a higher risk of suffering mental illnesses has been reported by people who also have difficulties paying their energy consumption bills (Public Health England 2014). Poor housing can also lead to children suffering from psychological symptoms, reduction of motivation, lower self-confidence and food insecurity (Evans, Saltzman, and Cooperman 2001; Harker 2006), affecting their rate of educational attainment, related to limitations on the amount of a comfortable and suitable living space to work and study (NEA and The Children's Society (for National Grid Affordable Warmth Solutions) 2015).

In conclusion, this review provides an overview of the multiple social vulnerabilities that influence EP, the impacts on households' health of living in EP, and the complexities of targeting vulnerable households with support. There remains a need to better understanding this issue of EP (Thomson, Snell, and Bouzarovski 2017) and to identify those households vulnerable to these situations. In this context, this paper presents the validation of an innovative index, which has been applied to different contexts such as Spain and England (Castaño-Rosa et al. 2019a; Castaño-Rosa, Solís-Guzmán, and Marrero 2018, 2020), for the analysis of vulnerability to EP by comparing its results to those obtained from a small-scale study undertaken in Salford, where energy-efficiency interventions were carried out. The results allow us to consider the IVH as a comprehensive approach to understand different levels of vulnerability to EP.

3. Methodology

The IVH (Castaño-Rosa, Solís-Guzmán, and Marrero 2018), which is based on previous EP indicators, gathers a number of social, economic, and environmental factors integrated and classified into four components: Monetary Poverty Indicator (MPI), Energy Indicator (EnI), Comfort Indicator (CI), and Health-Related Quality-Life Cost (HRQLC). Its four main components must be adapted to the UK context for this study. Furthermore, the validation of the assessment of households' health status provided by the IVH is presented by comparing its results with households' evidence in EP. To collect households' evidence, a survey was conducted in a small-scale case study undertaken in Salford, UK.

First, the components for the IVH are introduced. The MPI, based on the first component of the AROPE (At the risk of poverty or social exclusion) indicator which identifies those people at risk of poverty or social exclusion (European Commission 2018a), reflects the monetary vulnerability of a household based on the net income of the household. Sixty percent of median equivalised disposable income in the studied area, by means of the at-risk-of-poverty threshold set by the AROPE indicator according to Eurostat statistics, is used as a Monetary Poverty Threshold (MPT). Furthermore, a more precarious level of monetary poverty, which represents the social financial support provided to households in social exclusion, is represented by the Severe Monetary Poverty Threshold (SMPT), similarly to the MPT, this is set in the 40% of the median equivalised disposable income. The MPI is defined using Eq. (1):

$$\mathrm{MPI} = \mathrm{NI}/\mathrm{T} \tag{1}$$

where:

NI: Net Income of the analyzed household. This is calculated by subtracting housing and water and municipal solid waste management expenditures from the household gross income.

T: poverty threshold, which will depend on the country or region. A household is said to be in a monetary poverty or severe monetary poverty situation if its net income falls below the set threshold (MPI <1.00). The MPI allows us to both establish a comparative analysis with other country and region (Eurostat statistics are calculated annually for all EU Member States) and avoid false negative (exclude EP households from the analysis) and false positive (include those households who are not actually experiencing EP).

The EnI denotes the energy vulnerability of a household based on the required energy consumption of the dwelling (based upon modeled demand). The use of required energy consumption from an energy simulation avoids the effects of the characteristics, priorities, and customs of households on this value, as well as excluding those households who cannot afford minimum energy consumption due to the lack of monetary resources. Thus, households with an inadequate use of housing systems and Hidden Energy Poverty (HEP) (Rademaekers et al. 2016) can be analyzed. The energy consumption required (energy demand) for the type of building in the located area is used as Energy Indicator Threshold (EnIT). The EnI is defined using Eq. (2):

$$\mathrm{EnI} = \mathrm{EC}/\mathrm{MEC} \tag{2}$$

where:

EC: energy consumption required (modeled demand obtained from the software simulation).

MEC: median energy consumption required (energy demand) for the type of building in the area of study, according to official statistics. Therefore, the housing energy consumption is adequate if it is below the energy threshold or "admissible" (EnI <1.00), otherwise it is considered "inadmissible" (EnI >1.00).

The CI analyses the environmental dwelling vulnerability by using the percentage of hours in a situation of thermal comfort. This is a novel aspect when assessing thermal comfort in relation to EP. Traditionally single self-reported indicators of thermal comfort have been used for the analysis of EP, however, instead the CI uses the static method and the adaptive thermal-comfort model defined in the normative EN 15251:2007 (BS/EN 15251:2007n.d.) in winter and summer, respectively. Eighty percent of hours in a thermal comfort situation is determined to be the Comfort Indicator Threshold (CIT). This means that a person may be thermally uncomfortable for 5 h per day, and these hours are during sleeping hours (De Dear and Brager 2002). As recommended by the World Health Organization (WHO), two thermal comfort ranges are set according to the normative EN 15251:2007 (BS/EN 15251:2007n.d.): Category I for the living room, the temperature range between 21.0 and 25.5 ºC, and Category III for bedrooms, the temperature range between 18.0 and 27.0 ºC. Then, the CI result is "admissible" if the percentage of hours in thermal comfort is equal or higher than 80% (CI >80%). It should be noted that the criteria used for the definition of the CI meet the minimum temperatures recommended by the WHO; 21.0ºC in living rooms and 18.0ºC in bedrooms (Ormandy and Ezratty 2012).

The HRQLC provides an economic analysis of vulnerability to EP. This is the second novel aspect of the IVH; current EP indicators do not allow the costs associated with EP to be estimated and, consequently, to assess the societal impacts of current EP policies. The Quality Adjusted Life Year (QALY) takes into account both quality and quantity of life generated by healthcare interventions, an arithmetic calculation of life-expectancy as a measure of the quality expected of remaining years (Pinto and Rodriguez 2001). It is used here as the basis for the definition of the health state of a household for each level of vulnerability since it represents the potential impact of cold homes and, conversely, measures to improve them. The EQ-5D methodology, which is a standard measure of health state (Malek 2001; Phillips 2009; Torrance and Feeny 2009), allows for assessment of people's health state according to five factors (mobility, self-care, usual activities, pain/discomfort, and anxiety/depression) based on five-digit codes (QALY) by using the EQ-5D-5L Index Value Calculator (van Hout et al. 2012). The monetary value given to a QALY is set by the National Health Service (NHS) between £30,000–35,000 (Pinto and Rodríguez 2001), and this has been used to ascribe the HRQLC for each QALY defined in each level of vulnerability. The monetary value ascribed to a QALY is an economic measure based on willingness to pay for health improvements (Bashir, Eadson, and Pattison 2016). The process behind this is explained further in (Castaño-Rosa, Solís-Guzmán, and Marrero 2018).

A summary of the required data for the application of the IVH according to each component is provided in Table 1.

Table 2 shows the different levels of vulnerability of the IVH adapted to the British context: the thirteen levels of vulnerability resulting from combining the previously explained variables (monetary poverty, energy and comfort indicators) in accordance with the evidence presented by Castaño-Rosa, Solís-Guzmán, and Marrero (2018), the QALYs defined for each level of vulnerability depending on the variables results by using the EQ-5D-5L Index Value Calculator (van Hout et al. 2012), and the HRQLC ascribed to each QALY according to the monetary value given to a QALY by the NHS.

Then, the IVH is represented by Eq. (3):

Table 1. Required data for the IVH application (Source: Authors' own).

Component	Required data
Monetary Poverty Indicator (MPI = NI/T)	• Size and type of the household • Household income • Additional monetary benefits (social benefits, rental incomes, etc.) • Housing expenditure (rent or mortgage) • Other additional housing expenditures • Expenditure of water and municipal solid waste management
Energy Indicator (EnI = EC/MEC)	• Dwelling characteristics • Median energy consumption required by the type of dwelling analyzed in the located area • Energy consumption required by the analyzed dwelling • Energy Performance Certificate (EPC) rating of the analyzed dwelling • Standard Assessment Procedure (SAP) software
Comfort Indicator (CI ≥ 80%)	• Dwelling characteristics • Temperatures in the located area during the analyzed period • Indoor temperatures in the analyzed dwelling
Health-Related Quality-Life Cost	• Cost to the NHS per QALY

Table 2. Levels of vulnerability for the British context (Castaño-Rosa et al. 2019a).

Level	Variables			QALY	HRQLC (£)
1	MPI: NMP	EnI: Admissible	CI: Inadmissible	0.837	4890
2	MPI: NMP	EnI: Inadmissible	CI: Admissible	0.768	6960
3	MPI: NMP	EnI: Inadmissible	CI: Inadmissible	0.725	8250
4	MPI: MP	EnI: Admissible	CI: Admissible	0.721	8370
5	MPI: MP	EnI: Admissible	CI: Inadmissible	0.689	9330
6	MPI: SMP	EnI: Admissible	CI: Admissible	0.602	11,940
7	MPI: MP	EnI: Inadmissible	CI: Admissible	0.585	12,450
8	MPI: MP	EnI: Inadmissible	CI: Inadmissible	0.478	15,660
9	MPI: SMP	EnI: Admissible	CI: Inadmissible	0.312	20,640
10	MPI: SMP	EnI: Inadmissible	CI: Admissible	0.212	23,640
11	MPI: SMP	EnI: Inadmissible	CI: Inadmissible	−0.158	34,740
12	MPI: MP	EnI: Inadmissible*	CI: Inadmissible	−0.215	36,450
13	MPI: SMP	EnI: Inadmissible*	CI: Inadmissible	−0.337	40,110

NMP: No monetary poverty; MP: Monetary poverty; SMP: Severe monetary poverty.
* The household cannot afford a minimum energy consumption due to a lack of monetary resources.

$$\mathrm{IVH} = \mathrm{LV} \tag{3}$$

where LV is the level of vulnerability (Table 2). The calculation process is further explained in (Castaño-Rosa, Solís-Guzmán, and Marrero 2018).

3.1. *Survey*

The United Kingdom, mainly for its history and policies in addressing EP, as well as the availability of the data sources required for establishing a comparative analysis between the IVH and current EP indicators, may be considered as a reference country in the fight for reducing EP and is therefore an appropriate context to carry out the validation of the IVH.

The validation method consists of a comparison between the results provided by the IVH, in terms of households' health status, and those obtained from households' report within a small-scale study undertaken in Salford where an energy-efficiency intervention was previously carried out. The health status of those analyzed households within the case study was obtained by using a survey that asked households to assess their health status in relation to their monetary situation and the characteristics of the dwelling. Note that the health status of households was calculated according to the same criterion used to establish the different levels of vulnerability of the IVH (see explanation above), allowing a comparison of households' health status from both reported evidence and the IVH's assessment. The survey was defined based on the required data for the IVH's application: monetary situation and health status of householders, and characteristics of dwelling; gathering different energy vulnerability factors such as access, affordability, flexibility, energy efficiency, needs, and habits (see Annex 1). Note that due to concerns about breaching data protection regulations, only information about dwelling's characteristics, monetary situation and health status of households was collected; address and personal information were excluded from the survey. In this sense, this is one the limitations of this work; given the anonymity of the households, data collected during the survey could not be verified.

The survey was divided into two sections: section one gathered people and dwelling characteristics, while section two assessed the health status of people. In terms of the required data, in section one, household size, income, housing costs, council taxes, benefits, additional health expenditures, and tenure, were asked in eight different questions, providing the monetary data of households. Additionally, to obtain the minimum information about the characteristics of dwelling and calculate the energy and thermal comfort values, eight questions about dwelling type, building age, floor area, type of fuel to heat, and type of retrofit improvements installed were asked. Then, questions one to eight collected the required data to apply the MPI, and questions 9 to 16 gathered the minimum information about the characteristics of dwellings for the application of the EnI and CI.

Table 3 shows the composition of section one, detailing the different questions defined according to its application to energy vulnerability factors: access, affordability, flexibility, energy efficiency, needs, and habits (Bouzarovski, Petrova, and Tirado-Herrero 2014).

Section two, which was constituted by two main questions, was defined by using the EQ-5D methodology, according to the same criterion used to establish the different levels of vulnerability of the IVH (see Method section above). Households were asked to indicate their health status, before and after an energy-efficiency intervention, on the basis of five different levels of health (from level one, the best, without problems, to level five, the worst, with extreme problems) depending on how they perceive any problem according to the five factors defined in the EQ-5D methodology (mobility, self-care, usual activities, pain/discomfort, and anxiety/depression). Furthermore, a comments section was provided, allowing those households who could not describe their health status by using the options defined to briefly indicate how they felt. Subsequently, households were asked to describe their health status before and after an energy-efficiency intervention, allowing evidence of the household's health status to be collected. Comments from those households within the case study who provided additional information about their health status are listed below:

H1 (Owner): *Sometimes I felt sad and lonely. I had to be in my bedroom under bedding at all times.*

H2 (Owner): *I have mold on my windows and in my room. I feel better after the intervention, but I have still mold in my room.*

H3 (Owner): *Now, I can take a shower. Although, my room is still too cold to be comfortable. I can't control the times the radiators work. Everything is under lock.*

H4 (Owner): *Sometimes It is harder to sleep. I am in a bad mood next day.*

H5 (Owner): *We can't invite our friends because we're embarrassed by the mold. Although the installation of central heating has improved we are still struggling to control the mold, and it affects our health.*

H6 (Renter): *My accommodation doesn't provide me with a good place to study. It's very stressful. I always go to the library.*

H7 (Renter): *I'm a student. I avoid spending time in my accommodation. It's not a good home. It's a place where I sleep during my university period.*

Table 3. Section one of the survey: application to energy vulnerability factors (Source: Authors' own).

Questions	Application to energy vulnerability factors
1. What city/town/village are you living in?	Inability to access to minimum energy services and move to affordable one.
2. Indicate members of your household	Households energy requirements.
3. Could you indicate household income per month?	Lack of monetary resources.
4. Could you indicate your housing costs per month?	Role of tax systems, household needs, dwelling prices, assistance schemes.
5. Could you indicate your council taxes per month?	
6. What benefits are you currently receiving?	Lack of knowledge about available financial supports.
7. Could you indicate whether you have other additional health expenditures per month?	Inability to afford energy requirements for health reasons.
8. Are you? (Owner, private renter, social renter, other)	Inability to decide: type of fuel, retrofitting dwelling, thermal indoor characteristics.
Characteristics of dwellings	
9. What type of house do you live in?	Disproportionately high energy consumption: low level of maintenance and inadequate characteristics of dwelling.
10. In what year was your home built?	
11. What is the floor area of your home?	
12. What is the main fuel used to heat your property?	Inability to switch fuel used, lack of knowledge about other types of fuels, etc.
13. What type of retrofit improvements have been installed in?	Inability to decide energy-efficiency measures; lack of knowledge about optimal energy-efficiency interventions; inability to afford retrofitting improvements, etc.
14. What type of retrofit improvements have been installed for external walls?	
15. What type of retrofit improvements have been installed for windows?	
16. What type of retrofit improvements have been installed for the systems?	

Additionally, section two is divided into two parts: one defines households' health status before an energy-efficiency intervention; and another defines households' health status after the energy-efficiency intervention. Each response can then define two different scenarios depending on whether an energy-efficiency had been implemented, and what type of measure had been installed.

As an example, Table 4 shows the analysis of the information provided by one household (H1 above) about its health status from section two. According to the health levels provided by "H1", by using the EQ-5D methodology (van Hout et al. 2012), the resulting QALY before and after the energy-efficiency intervention is 0.289 and 0.668, respectively. In more detail, "H1" indicated no mobility problems; severe problems performing self-care and usual activities; moderate pain/discomfort problems; and severe anxiety/depression problems before the energy-efficiency intervention. In contrast, after the energy-efficiency intervention, this household "H1" indicated no mobility problems; slight problems performing self-care activities; no problems performing usual activities; slight pain/discomfort problems; and moderate anxiety/depression problems.

3.2. *Case study*

The case study was located in a small area within the city of Salford. This case study is defined based on the IVH's application to the British context (similar households, dwelling, socio-economic and climatic characteristics) (Castaño-Rosa et al. 2019a) underpinning this work's results and justifying its value. The representativeness of the case study was considered sufficient to reach data saturation: income levels, resource availability, and socioeconomic characteristics do not vary significantly within the city of Salford (Sherriff 2016; Sherriff and Martin 2016;

Table 4. Health-status analysis with report from household "H1" (Source: Authors' own preparation based on the EQ-5D methodology).

Factors	Health levels	Illness	Score	QALY
Before the intervention				
Mobility	12345	No problems	14434	0.289
Self-care	12345	Severe problems		
Usual activities	12345	Severe problems		
Pain/Discomfort	12345	Moderate problems		
Anxiety/Depression	12345	Severe problems		
After the intervention				
Mobility	12345	No problems	12123	0.668
Self-care	12345	Slight problems		
Usual activities	12345	No problems		
Pain/Discomfort	12345	Slight problems		
Anxiety/Depression	12345	Moderate problems		

Table 5. Typologies of households analyzed (Source: Authors' own).

			Nº members		
Type of dwelling	Built year	Floor area (m^2)	Adults	Children	Number households
Terraced	Before 1919	50–69	1	-	1
			2	-	2
			2	1	1
		70–89	1	-	6
			2	-	9
			2	1	7
		90–109	2	1	1
		> 110	2	-	1
	1965-1980	< 50	2	1	1

Sherriff, Martin, and Roberts 2018). This means that additional data, and/or a large sample size, would not provide relevant outcomes to the evaluation (Burmeister and Aitken 2012; Quinn Patton 2014; Roberts et al. 2016). This was composed of 29 households living with low incomes, but whose dwellings had been subject to energy-efficiency improvements. Note that the 29 households were selected amongst those who filled out the defined survey and whose provided data (anonymous households; address and personal information were excluded from the survey) was suitable for the validation analysis. This survey was available online from February to March 2018, the most severe season in the UK (Department of Energy & Climate Change (DECC) 2019). The archetypal housing type in the case study area was pre-1919 terraced housing and terraced housing built between 1965–1980. Table 5 shows the typologies of dwellings analyzed (depending on the built year and floor area), the number of members that comprised each household (adults and children, less than 14-years old), and the number of households analyzed for each group.

Additionally, Table 6 shows the data of dwelling constructions and the characteristics of dwelling systems provided in the households' survey.

Figure 1 shows graphically the validation method: section one is used to collect the required information to apply the IVH (characteristics of people and dwellings) and section two to assess the quality of households' life (QALYs), leading to a comparative analysis between the QALYs provided by the IVH and households' report.

Table 6. Characteristics of the analyzed dwellings (Source: Authors' own).

Element	Description	System	Description
Walls	Solid brick, as built, no insulation	Heating	Room heaters, mains gas
Roof	Pitched without insulation		Portable electric heaters for most rooms
Floor	Reinforced concrete raft with no insulation added	Domestic hot water	Electric instantaneous equipment at the point of use
Ground floor	Suspended timber above a ventilated underfloor void		Gas instantaneous at the point of use
Windows	Double glazed windows in wooden frames	Others	Electricity
Party walls	Same as external walls		

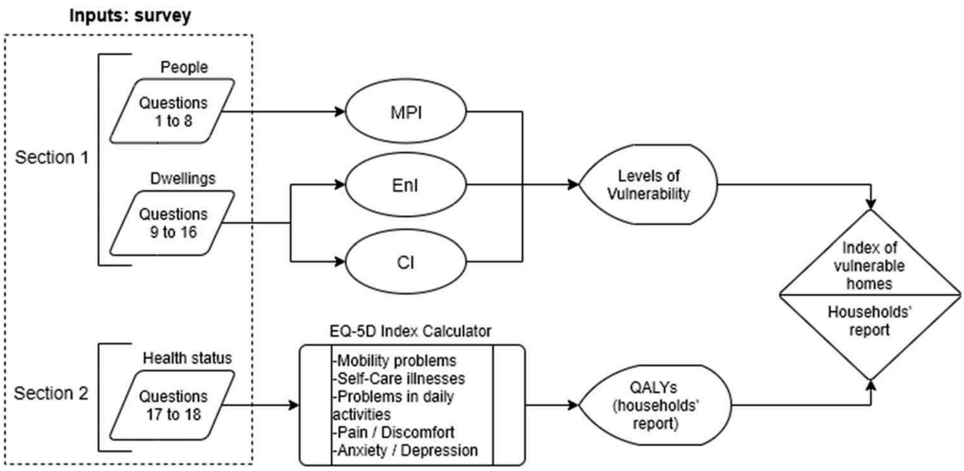

Figure 1. Validation method.
Source: Authors' own preparation.

4. Results

After analyzing the response of the 29 households who responded to the online survey, a total of 58 responses about households' health status was collected (29 responses before an energy-efficiency intervention and twenty-nine responses after it). This section presents the results of the application of the IVH in terms of QALYs before and after the energy-efficiency intervention reported for the households in the survey.

4.1. *Before an energy-efficiency intervention*

This section shows the IVH's results and households' report before carrying out an energy-efficiency intervention (initial state), leading to 29 responses about households' health status.

4.1.1. *Monetary Poverty Indicator (MPI)*

According to the explanation provided above, 60% and 40% of the median equivalised disposable income for one person in the UK in 2017, according to Eurostat statistics (Eurostat n.d.), was used as the MPT and SMPT, respectively. Table 7 shows the thresholds set for the UK case study according to Eurostat statistics.

Note that data about households' net income used to apply the MPI was obtained from the survey.

Table 7. Monetary thresholds for the UK (Source: Authors' own analysis).

Household	MPT	SMPT
One adult	£11,044	£7362
Two adults	£16,566	£11,043
Two adults and one child	£19,879	£13,252
Two adults and two children	£23,192	£15,460
Two adults and three children	£26,506	£17,669

4.1.2. *Energy indicator (EnI)*

The energy threshold was set at the median energy consumption required by the different typologies of dwellings analyzed in the case study, as detailed in the annual fuel poverty statistics in the UK (Department of Energy & Climate Change (DECC) 2019). The required energy consumption of each dwelling was obtained from the modeling simulation by using the energy modeling package SAP (Building Research Establishment 2013). The required data to define the different dwellings analyzed in the modeling software was obtained from the survey's first section and the energy performance certificate database (Department For Communities and Local Government n.d.). Additionally, the operational parameters were set on the basis of those households who could spend most of their time at home, for instance, students, unemployed and disabled people, according to the SAP guidance (from 7 am until 9 am in the morning and 4 pm until 11 pm in the evening) (Building Research Establishment 2013). Note that orientation and number of occupant factors do not have a significant

Table 8. MPI, EnI, and CI results depending on the analyzed households.

MPI results

Type of dwelling	Built year	Floor area (m^2)	Nº members: Adults	Nº members: Children	Number	Results
Terraced	Before 1919	50-69	1	-	1	Poverty
			2	-	2	Severe Poverty
			2	1	1	Poverty
		70-89	1	-	1	Poverty
			1	-	5	Severe Poverty
			2	-	3	Poverty
			2	-	6	Severe Poverty
			2	1	1	Poverty
			2	1	6	Severe Poverty
		90-109	2	1	1	Poverty
		> 110	2	-	1	Poverty
	1965-1980	< 50	2	1	1	Poverty

EnI results

Type of dwelling	Built year	Floor area (m^2)	Energy consumption	Energy threshold	Results
Terraced	Before 1919	50-69	16,725	13,793	Inadmissible
		70-89	22,347	17,699	Inadmissible
		90-109	27,969	20,532	Inadmissible
		> 110	30,921	25,648	Inadmissible
	1965-1980	< 50	11,070	9,644	Inadmissible

CI results

Type of dwelling	Built year	Floor area (m^2)	Results (Summer)	Results (Remainder)
Terraced	Before 1919	50-69	Admissible	Inadmissible
		70-89	Admissible	Inadmissible
		90-109	Admissible	Inadmissible
		> 110	Admissible	Inadmissible
	1965-1980	< 50	Admissible	Inadmissible

Table 9. Households' QALYs according to the IVH and survey for 1 year (Source: Authors' own).

Type of dwelling	Built year	Floor area (m^2)	Nº Household	Modeled (IVH)	Reported (Survey)
Terraced	Before 1919	50–69	2	0.552	0.628
			2	0.151	0.312
		70–80	5	0.552	0.253
			15	0.151	0.343
		90–109	1	0.552	0.725
		> 110	1	0.552	0.675
			1	0.151	0.368
	1965–1980	< 50	1	0.151	0.289
			1	0.552	0.573

Standard deviation: Modeled ≈ 0.1004; Reported ≈ 0,0946.

impact in the final energy consumption of those dwellings with the same year and floor area obtained from the dwelling simulation (see Table 9).

4.1.3. *Comfort Indicator (CI)*

The comfort threshold was set at 80%. Two ranges of comfort, by using the normative EN 15251:2007 (BS/EN 15251:2007n.d.), were set depending on the analyzed living space: Category I, for living room; and Category III, for bedroom. To simulate 1 year of operation and indoor temperature, the DesignBuilder software ("DesignBuilder" 2017) joint to the dynamic thermal-comfort software EnergyPlus 7.0 ("EnergyPlus" 2017) was used.

Following Table 8 shows the MPI results depending on the number of members in each household, the EnI results depending on the typologies of dwellings analyzed, and the CI results depending on the analyzed period, summer, and remainder (autumn, winter, and spring), for each of the analyzed dwelling.

Table 9 shows the QALYs for 1 year depending on the characteristics of dwelling according to the IVH (modeled – after applying Eq. (3)) and the survey (reported) obtained from the 29 households analyzed.

4.2. *After an energy-efficiency intervention*

This section shows the IVH's results in terms of QALYs after an energy-efficiency intervention. The retrofitting interventions consisted of combining different energy-efficiency measures: solid wall insulation, loft insulation, and UPVC (unplasticized polyvinyl chloride) double glazing windows, and these were broadly similar for all households. Information about what kind of energy-efficiency measures had been installed in each dwelling was provided by those households who filled out the online survey (see Table 3).

Table 10. Households' QALYs after an energy-efficiency intervention for 1 year (Source: Authors' own).

Type of dwelling	Built year	Floor area (m^2)	Nº Household	Modeled (IVH)	Reported (Survey)
Terraced	Before 1919	50–69	2	0.770	0.800
			2	0.500	0.681
		70–80	5	0.770	0.799
			15	0.500	0.643
		90–109	1	0.770	0.834
		> 110	1	0.770	0.775
			1	0.500	0.561
	1965–1980	< 50	1	0.500	0.668
			1	0.770	0.809

Standard deviation: Modeled ≈ 0.0994; Reported ≈ 0,0794.

As was explained above, the required energy consumption of the dwellings after the energy-efficiency intervention was obtained from the modeling simulation by using the energy modeling package SAP (Building Research Establishment 2013). Note that the required energy consumption was reduced for all dwellings to almost half the initial value, leading the results of the EnI to be "admissible". Regarding the results of the CI after the energy-efficiency intervention, although the percentage of hours in thermal comfort was increased, these were the same as detailed in Table 8. These results show the higher situation of vulnerability to EP all year round (winter, spring, and autumn) in England, due to longer cold period, than in other countries with warmer climates such as Spain (Castaño-Rosa, Solís-Guzmán, and Marrero 2018).

Note that the monetary situation of the analyzed households remained the same, since only the technical characteristics of dwellings were changed. Table 10 shows the IVH's results (modeled) in terms of QALYs depending on the characteristics of dwelling in relation to the QALYs obtained from 29 households` report (survey) after carrying out an energy-efficiency intervention.

5. Discussion

After analyzing the results provided by the IVH and the survey, four different groups of households were defined on the basis of the values of QALY for 1 year according to the IVH's results before and after an energy-efficiency intervention: 0.552 (10 households); 0.151 (19 households); 0.770 (10 households); and 0.500 (19 households), orange bars in Figure 2. The average QALY value from the reports of those households included in each of the four groups was used to establish the comparative analysis. The result is that group one, composed of 10 households, had a QALY's value of 0.552 and 0.591 according to the IVH and households' report, respectively; group number two, composed of 19 households, had a QALY's value of 0.151 and 0.279 according to the IVH and households' report; group number three, composed of 10 households, had a QALY's value of 0.770 and 0.787 according to the IVH and households' report; and group number four, composed of 19 households, had a QALY's value of 0.500 and 0.500 according to the IVH and households' report.

Figure 2 presents graphically the relationship between the values of QALYs provided by the survey (blue bars) and the IVH (orange bars), depending on the four different groups defined. Furthermore, the resulting deviation (gray bars), represents the difference between the assessment provided by the IVH and perceptions of the householders. The negative value of the deviation shown in Figure 2 means that the assessment of households' health status provided by the value of QALY based on the IVH shows a slightly worst health status of the households than what was reported by the householders.

To evaluate whether the assessment made by the IVH is acceptable as a way of understanding the possible different levels of EP vulnerability, an admissible deviation was established. Here, to establish the admissible deviation, in accordance with the evidence presented in the Literature review section, it is

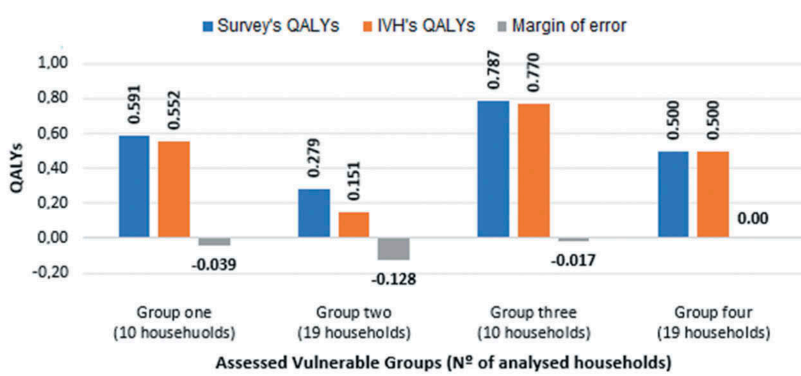

Figure 2. Comparative analysis: the IVH & households' report.
Source: Authors' own.

considered that a person could have at least slight pain or discomfort problems in some period for 1-year due to issues such as personal and professional problems, health issues (such as flu or cold) and unexpected expenditures, leading to the conclusion that 0.163 would be an appropriate minimum value of QALY that a person could lose for 1 year, in accordance with the EQ-5D methodology index (van Hout et al. 2012). Referring to Figure 2, it can be said that the resulting deviation for each of the four-assessment group is admissible since the deviation's values for groups one, two, three, and four are 0.039, 0.128, 0.017, and 0.00, respectively, and the admissible deviation is 0.163. It is important to highlight that the deviation's value of 0.00 for group four implies that the reported health status of 19 out of 58 households would be the same as the health status modeled by the IVH.

Additionally, it should be highlighted that the IVH captures the improvement of households' health status after an energy-efficiency intervention by comparing results from Tables 8 and 9. Before an energy-efficiency intervention, the values of QALYs provided by the IVH were 0.151 (10 households) and 0.552 (19 households). On the contrary, after an energy-efficiency intervention, the values of QALYs provided by the IVH for the same households were 0.500 (10 households) and 0.770 (19 households). Following our earlier exposition of the relationship between EP and health, this improvement in the IVH's results can be assumed to be caused mainly by a better thermal comfort in the house, decreased stress in relation to energy bills, and a reduction in the household's energy expenditure following the intervention.

6. Limitations

Involving households in research projects was the main challenge in relation to obtaining the data needed for the evaluation of the IHV's results. This can be due sensitivities around being asked about personal issues such as income, expenses, and poverty. For example, research involving mental health service users and fuel poverty found that households could be uncomfortable with an advisor coming to their home, or with talking to others about health and financial issues (Sherriff 2017). It should be borne in mind that that fuel poor older people and vulnerable groups, in particular, may not have internet access at home and were therefore unable to easily reply to the survey. However, an online survey was the only option to get a wide spectrum of views with limited time and budget. Note that, due to the small sample size, these results must be carefully considered and interpreted. Address and personal information was excluded from the survey (households are anonymous), making it difficult to verify the collected data, and this is therefore another limitation of this work. An attempt to collaborate with different associations that work in the housing sector (such as those carrying out activities such as energy-efficiency interventions, information sessions for more vulnerable households, and conferences) was sought, but this element of the research was unsuccessful. Particular limitations experienced with this part of the study included the potential role of private companies (and concerns about negative publicity) as well as concerns about breaching data protection regulations.

Additionally, it is essential to bear in mind that people's behavior in certain situations is impossible to predict, due to the wide range of factors involved in their relationship with energy consumption such as culture, age, educational level, physical and psychological aspects (Kearns, Whitley, and Curl 2019). This has implications for estimating energy consumption and indoor temperatures obtained from the simulation, even when using standard operation patterns and climatic data from the IWEC data of EnergyPlus software, since these can vary depending on household and dwelling characteristics. This implies that these results should be seen as indicative and also highlights the need for further research to validate the defined methodology through a bigger case study.

7. Conclusions

EP is a multidimensional issue composed of a wide diversity of factors that make it difficult to understand the relationship between vulnerability to EP and households' quality of life. In this sense, this paper aims to build a limited and real-world sample of evidence that helps to evaluate the validity of the assessment of households' health status provided by the IVH and to allow us to consider the IVH as a comprehensive approach to understanding different levels of vulnerability to EP. To do this, and the novelty of this work, a methodology for collecting data through surveys is proposed, leading to calculate the IVH and, consequently, to compare its results with households' evidence. Noting then that results from this survey must be carefully considered due to the subjective, culturally, and psychological aspects of households' energy consumption (Zhang et al. 2018), the vulnerability to EP (Kearns, Whitley, and Curl 2019) and the relatively small sample size in this study. Sample size directly influences research results, and they must therefore always be cautiously interpreted (Faber and Fonseca 2014). Furthermore, households were anonymous, and the response rate could not be verified. In this sense, to understand the validity of the assessment of households' health status conducted by using the IVH, it is essential to consider that people's behavior in determinate situations is impossible to predict, due to the wide range of factors involved (including culture, age, educational level, physical and psychological aspects) (Delzendeh et al. 2017), leading therefore to difficulty in establishing different situations of vulnerability.

The literature review shows the multiple social vulnerabilities that influence EP, the complexities of targeting vulnerable households, and the need to better understand EP. The different energy vulnerability factors taken into consideration in the design of the household survey are defined, allowing us to gather strong households' evidence and get a wide spectrum of EP vulnerability situations.

The comparative analysis between the assessment of households' health status according to the IVH and reported evidence (obtained from the survey) before and after the energy-efficiency intervention implies that the assessment provided by the IVH about the health status of those households identified to be in a vulnerable situation to EP is acceptable.

In this context, this work considers it essential to take into consideration the behavior of households in order to analyze and understand the validity of these results. Concepts like the "Take-back" effect (Stafford, Gorse, and Shao 2011), which is the tendency of households to increase their comfort, as well as, potentially, their energy consumption, because they believe that their dwellings are now more energy efficient, as well as behavioral and psychological mechanisms of coping (Butler and Sherriff 2017) imply that the IVH cannot be considered as a statistically and robust conclusion, but is rather an indicative approach to understanding households' vulnerability. Further research will therefore need to take into account more subjective and less quantifiable aspects.

In the end, there is a range of indicators and measures that assess energy poverty, and even vulnerability in relation to monetary, energy, thermal comfort, and environmental factors. However, there is no indicator that assesses vulnerability to EP by gathering all those factors and then providing an economic analysis of vulnerability to EP in terms of the quality of life of householders and related health implications (Castaño-Rosa et al. 2019b). This paper adds to other evidence (Castaño-Rosa 2018; Castaño-Rosa, Solís-Guzmán, and Marrero 2018, 2020) that the IVH offers a way of assessing household vulnerability to multiple factors implicated in energy poverty. This study provides an indication that the IVH is a comprehensive response to understanding different situations of vulnerability to EP, can provide a reliable assessment of households' quality of life at a neighborhood level and forms the basis for future research to investigate its potential at larger scales.

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Annexe 1

1. What city/town/village are you living in?

____

2. Indicate members of your household
Adults (between 16-65 years old) ____
Adults (+65 years old) ____
Children (<16 years old) ____
Male _____ Female____

3. Could you indicate household income per month
□< 1100 £ □1100-1400 £ □1400-1600 £
□1600-1800 £ □1800-2100 £ □> 2100 £

4. Could you indicate your housing costs (rent or mortgage) per month
□None □< 500 £ □500-700 £
□700-900 £ > □900 £

5. Could you indicate your council taxes per month
□Don't know □< 50 £ □50-150 £
□150-250 £ □> 250 £

6. What benefits are you currently receiving?
Yes No Don't know

- Bereavement Allowance
- Career's Allowance
- Child Benefit
- Child Tax Credit
- Disability Living Allowance
- Allowance Work Related Activity Group
- Employment and Support Allowance
  Support Group
- Housing Benefit
- Incapacity Benefit
- Income Support
- Industrial Injuries Disablement Benefit
- Jobseeker's Allowance
- Maternity / Paternity Allowance /

Adoption Pay

- Personal Independence Payment
- Statutory Sick Pay
- Universal Credit
- Working Tax Credit
- Other

7. Could you indicate whether you have other additional health expenditures per month (disable relative expenditure, health drug expenditure, health insurance, etc.)
□Don't know □< 50 £ □50-150 £
□150-250 £ □> 250 £

8. Are you?
□Owner □Private renter □Social renter
□Other

9. What type of house do you live in?
□Detached □Semi-detached □Mid-terraced
□End-terraced □Terraced □Other

10. In what year was your home built?
□Before □1919 1919-1944 □1945-1964
□1965-1980 □1981-1990 □1991-2003
□Post 2004

11. what is the floor area of your home?
□Don't know □less than 50 m^2 □50-69 m^2
□70-89 m^2 □90-109 m^2 □110 m^2 or more

12. What is the main fuel used to heat your property?
□Don't know □Mains gas □Main electricity
□Biomass □Oil □House coal

13. What type of retrofit improvements have been installed?

	Uninsulated	Insulated
Roof		
Ground floor		

14. What type of retrofit improvements have been installed for external walls?
Uninsulated
Cavity filled wall insulation
Solid wall insulation

15. What type of retrofit improvements have been installed for windows?
Unchanged
Double glazing
Double glazing low emission

16. What type of retrofit improvements have been installed for the systems?

	Unchanged	New condensing boiler	Other
Heating			
Hot water			

17. What other retrofit improvements have you had or made?

<u>Health perception</u>

The following section tries to estimate the minimum health-status improvement of household before and after the energy-efficiency interventions. Please indicate your health status on the base of 5 different levels of health (1 the best and 5 the worst) depending on you perceive any problems. If your health status can't be described by one of the options, indicate shortly how do you feel at the end section comments.

18. Before the energy-efficiency intervention

	No problems	Slight problems	Moderate problems	Severe problems	Extreme problems
Mobility (e.g. carry out different activities in particular rooms of the house)					
Self-care (e.g. washing, dressing, etc.)					
Usual activities (e.g. work, study, housework, family or leisure activities)					
Pain/Discomfort					
Anxiety/Depression					

19. After the energy-efficiency intervention

	No problems	Slight problems	Moderate problems	Severe problems	Extreme problems
Mobility (e.g. carry out different activities in particular rooms of the house)					
Self-care (e.g. washing, dressing, etc.)					
Usual activities (e.g. work, study, housework, family or leisure activities)					
Pain/Discomfort					
Anxiety/Depression					

20. Commentary: