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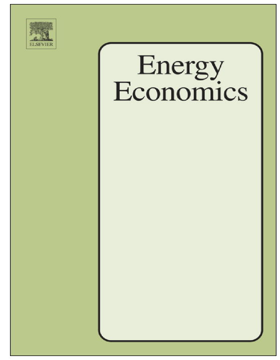

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PII: S0140-9883(21)00427-8
DOI: https://doi.org/10.1016/j.eneco.2021.105551
Reference: ENEECO 105551

To appear in: *Energy Economics*

Received date: 25 January 2021
Revised date: 25 August 2021
Accepted date: 29 August 2021

Please cite this article as: D. Deller, G. Turner and C.W. Price, Energy poverty indicators: Inconsistencies, implications and where next?, *Energy Economics* (2018), https://doi.org/10.1016/j.eneco.2021.105551

Energy Poverty Indicators:Inconsistencies, Implications and Where Next?

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August 2021

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Abstract: Energy Poverty in all climates and economies is recognised as problematic, whether related to insufficient warmth or inadequate cooling, making its definition and the identification of which households are most at risk of central importance. Different definitions of Energy Poverty identify not only varying numbers of households at risk, but households with different characteristics, and provide an ambiguous basis for both academic studies and policy design. To confirm and illustrate these universal issues we use a large dataset from the United Kingdom to demonstrate how three commonly used indicators, including two based on official measures, can imply very different targeting policies. In particular, our rich panel dataset confirms and extends the finding that older households are more likely than their younger counterparts to be identified as energy poor when using expenditure-based indicators, but are less likely to self-identify as unable to afford adequate warmth. Similar discrepancies between Energy Poverty indicators relate to the presence of children in a household, household size, and geographical location. This methodological and historical illustration from the UK, which has recently introduced its third official definition of Energy Poverty in a decade, is relevant to any country seeking to measure and address the plight of households who struggle to achieve desired in-home temperatures. The observed contradictions emphasise the importance of obtaining direct evidence on the fundamental underlying issues encapsulated by Energy Poverty. Where in-home temperatures are the focus this means complementing the current measures with information on achieved temperatures and households' temperature preferences.

KEY WORDS: Energy Poverty; Fuel Poverty; Home temperatures; United Kingdom; Subjective well-being; Measurement issues

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1. Introduction[1]

Understanding the phenomenon of Energy Poverty[2] (EP) among households requires consistent definition and measurement, both as a basis for future academic studies and to design and assess effective policies, whether in cold or warm climates. The definition and measurement of EP influence conclusions about its prevalence, the targeting of policies to reduce it and assessments of policy effectiveness, including in developing countries, where the challenge and concepts of EP differ fundamentally from their evolution in Europe and North America (see for example Pachauri and Spreng (2011)). The variety of current definitions, and their differing identification of households most at risk of Energy Poverty, mean that analysis and policy development is contingent on the metric chosen.

To understand and illustrate the challenges, we take advantage of a rich historical dataset to explore the overlap between three potential definitions: two expenditure-based measures which are closely related to official classifications; and one based on households' own assessment of whether they cannot afford adequate warmth in the home. This panel dataset provides a distinct opportunity, not previously reported in the literature, to analyse energy expenditures and perceptions of heat affordability for the same households over eight years. Its originality relates to several dimensions: (i) the number of EP indicators that can be compared; (ii) having observations relating to each metric for the same households from multiple years; and (iii) the large sample size. The analysis explores the complex relationships between different indicators of EP in a more robust way than is possible using more aggregated data or information from surveys applied to different households. We confirm stark differences between the alternative measures of EP, most markedly for older households, households containing children and those living in different geographical areas. The contribution in relation to other literature on EP is explored further in the next section.

While the methodological issues raised for academic assessment and for policy design are generally applicable, the specific context is relevant because the United Kingdom was an early adopter of the Energy (or Fuel) Poverty concept, and has recently introduced its third definition of Fuel Poverty in less than a decade. Like our affordability measure, this latest indicator does not include an expenditure component, and so differs fundamentally from its two predecessors. That the UK has frequently changed its Fuel Poverty definition indicates the extent to which measurement of EP remains unsettled and provides an example to other regimes on adopting a particular EP definition.

[1] Abbreviations: BEIS, Department for Business, Energy and Industrial Strategy; BHPS, British Household Panel Survey; DECC, Department for Energy and Climate Change; EHS, English Housing Survey; ENEX, energy expenditure; ENEXShr, energy expenditure as a share of household income; EP, energy poverty; IAAW, inability to afford adequate warmth in the home.

[2] We make no distinction between energy and fuel poverty.

Our analysis confirms the intricacies of relationships between different indicators, leading to fundamental questions about the underlying household experience being measured by each indicator. The data come from the British Household Panel Survey and cover the period 2001 to 2009, a period when the UK implemented several energy poverty interventions, including a universal age-related financial benefit to offset heating costs. The contradictory results for older households therefore hold particular relevance for UK policy.

EP has attracted political attention because low-income households devote a much higher proportion of their income to energy, on average, than do richer households. While such a pattern is common for ‘necessities’, it is particularly stark in energy, see Deller and Waddams Price (2017) for example. The negative consequences of EP are well established, in particular, those of poor health, whether the issue is inadequate or excess heat. Indeed, the initial development of the concept was related to health concerns, as highlighted in the discussion in Section 2.

The challenges of identifying energy poor households and debates about different statistical definitions of EP are well established, for example Waddams Price et al. (2012); Miniaci et al. (2014); Thomson et al., (2017) and Tirado Herrero (2017). The British Household Panel Survey (BHPS) enables the most detailed comparison yet of perception- and expenditure-based EP indicators[3]. The analysis in this paper confirms a limited overlap between the indicators and demonstrates that each measure identifies as energy poor households with noticeably different socio-economic characteristics, reflecting the complexity of their lived experience as suggested by Longhurst and Hargreaves (2019). To move research and policy forward, additional information is needed both on the temperatures achieved within households and how these reflect each household’s preferences if the objective is to identify households living in excess cold or heat.

This paper takes the opportunity of a much larger, richer and more representative multi-year dataset to build on Waddams Price et al. (2012). The analysis considers three EP indicators. One is perception-based, namely reporting an inability to afford adequate warmth in the home (IAAW), providing an intuitive self-assessment of living in a cold home. The other two indicators are based on household-reported energy expenditure. The first is that energy expenditures (ENEX) exceed 10% of income (10% EP); and the second is a Low Income-High Cost (LIHC) indicator for households who spend more than the median expenditure on energy, and whose residual income (after that expenditure is deducted) falls below 60% of the median level. These two expenditure-based indicators mirror the official indicators used by the government to assess EP in England, and have been widely used in the academic literature. The expenditure based indicators of EP derived here differ in an important respect from England’s official estimates which are based on engineering models of the expenditure required to achieve particular in-home temperatures. Instead, the measures derived and analysed in this paper are based on households’ reports of their own expenditure, representing an important aspect of the household experience.

The three indicators generate very different frequencies of households in EP, with many fewer households declaring IAAW than are identified by the expenditure-based metrics. The small

[3] We use ‘perception-based’ and ‘expenditure-based’ to avoid terms that could be (mis-)interpreted as implying a judgement about the indicators’ legitimacy. Perception-based covers indicators previously termed ‘subjective’ or ‘consensual’, while expenditure-based covers indicators previously termed ‘objective’.

overlap between indicators is striking. No more than 5% of those identified as energy poor by the two expenditure-based indicators report IAAW; and fewer than 45% of those reporting IAAW are identified as energy poor according to the LIHC indicator[4].

Our analysis of pooled cross-section logit regressions complements descriptive statistics to identify a set of exogenous household characteristics which are associated with each EP indicator. This confirms the fundamental contrast between self-assessed inability to afford adequate warmth and the expenditure-based metrics. The association with age reveals the most striking difference: households with a head aged 65 or over show a lower probability of reporting IAAW relative to younger households, but a higher risk of being energy poor according to either of the expenditure-based indicators. These differences are particularly marked for households with heads aged over 75 years. Similarly, households with children are more likely to be classified as energy poor by either expenditure based measure, but are no more likely than those without children to declare IAAW. Geographical location also has different associations with the alternative indicators: the incidence of expenditure-based EP is higher in Scotland and Northern Ireland but there is no significant difference between countries in reporting IAAW.

These differences do not lead us to conclude that one indicator is 'superior' to others. In particular, we are cautious about concluding that expenditure based metrics necessarily overstate the prevalence of households struggling to afford warmth; such conclusions often rely on additional assumptions. For example, older households may be less likely to report IAAW because they perceive lower temperatures as adequate, or feel less comfortable admitting to 'problems'. Such cases highlight the important influence of social and cultural factors for the measurement and understanding of EP. While some of these issues are addressed by using modelled ENEX, as in the official English statistics, such modelled data generate new issues, including the accuracy of the models, and their independence from householders' individual temperature preferences[5].

While the concept of EP in the UK has been associated with access to warmth in cold homes since its inception, efforts to measure in-home temperatures since the mid-1990s have been limited, despite the encouragement of the Hills report in 2012. Obtaining such data on the necessary scale has been widely viewed as a significant obstacle, but the development of smart thermostats, and other smart temperature recording devices, offer promising routes to obtain such data[6]. Supplementary data on in-home temperature measurements and temperature preference information needs to be combined with data generating the current EP indicators to understand why different EP indicators present such varied pictures and to address the underlying issues.

The paper proceeds as follows: Section 2 reviews the existing literature and Section 3 describes the data and methodology; Section 4 reports descriptive statistics and regression results, whose robustness is discussed in Section 5; and Section 6 concludes.

[4] 30% for 10% EP. See Figures 6 and 7 in Appendix 2.
[5] For example, see Deller and Waddams Price (2017) and Summerfield et al. (2019).
[6] Gouveia et al. (2018) provide an example of in-home temperature measurement in Italy

2. Related literature

The phrase Fuel Poverty (broadly equivalent to EP) was described by Bradshaw and Hutton (1983) as the 'inability to afford adequate warmth at home', extending unpublished work by Hancock and Isherwood (1979) which aimed "to identify those consumers for whom the payment of fuel bills raises difficulties and to examine their characteristics in terms of income, age etc." Boardman developed the concept in her 1991 book, using the focus on disproportionate energy expenditure by low income households as the basis for defining 10% EP; this was based on findings (from the 1988 UK Food and Expenditure Survey) that the 30% of households with the lowest incomes devoted on average 10% of their income to energy, about twice the median proportion for the population as a whole. Much of the initial academic discussion in the UK and developed economies focused on this definition and other expenditure-based measures, although very different measures have been used to assess EP in many less developed countries (see, for example, Pachauri and Spreng (2011)). Within the UK, the decision to change the English fuel poverty metric from 10% EP to an LIHC definition was driven by Hills (2012) and received comment from Moore (2012) and Liddell et al. (2012). For Germany, Heindl (2015) reviews different expenditure-based metrics and how their prevalence varies across households with different structures, while Heindl and Schuessler (2015) assess these metrics' statistical properties. Romero et al. (2018) compare expenditure-based indicators for Spain, including one based on a minimum income standard, and Faiella and Lavecchia (2021) assess several expenditure-proportion and LIHC definitions for Italy.

The challenges of comparing expenditure-based EP across nations, for example between EU member states, stimulated increasing comment on perception-based metrics and how these related to the more established expenditure-based measures. Within the UK, the main previous study comparing an expenditure- and a perception-based metric is Waddams Price et al. (2012), which showed considerable differences between households who were 10% energy poor and those who felt unable to afford energy. Our analysis uses data from around four times as many households as Waddams Price et al., and over 20 times more observations, enabling increased sensitivity and robustness. BEIS (2021) confirms that overlap between perception-based and expenditure-based indicators continues to be limited in England.

Beyond the UK, comparisons between expenditure- and perception-based EP are presented for Spain by Phimister et al. (2015); for Greece by Papada and Kaliampakos (2016) and Ntaintasis et al. (2019); for Belgium by Meyer et al. (2018); for the US by Agbim et al. (2020); for France by Fizaine and Kahouli (2019); for Poland by Sokolowski et al. (2020); and for the Republic of Ireland by Scott et al. (2008). Direct comparison of the results is difficult due to the different wording of the perception-based indicators and variations in the definitions of the expenditure-based indicators, although all these studies find a consistent lack of overlap between the measures.

The present paper adds to the findings of Phimister et al. (2015), Papada and Kaliampakos (2016), Meyer et al. (2018), Ntaintasis et al. (2019) and Sokolowski et al. (2020) by including multivariate logit regressions to identify the main exogenous household characteristics associated with each EP indicator when other factors are held constant. While Scott et al. (2008) run logit regressions to identify factors associated with 10% EP and a composite perception-based indicator, the data for each indicator come from separate Irish surveys. Our analysis avoids the risk that variations in relationships across indicators may reflect differences in sampling, variable definitions and/or households' unobservable characteristics; by using a single panel survey as the source for all the the different EP indicators, direct comparisons can be made for the same set of households. Comparing EP rates across Europe, Healy and Clinch (2002) and Thomson and Snell (2013) use regressions to analyse the household characteristics associated with perception-based and/or proxy indicators of EP. Both studies include an 'inability to afford adequate warmth' indicator. Healy and Clinch (2002) report that younger households are more likely to report an inability to achieve adequate warmth.

These papers form part of a wider debate about the best way to measure EP among households. Figure 1 of Deller (2018) provides an overview of how energy affordability (EP) measures can be split between: (i) ENEX indicators, including LIHC measures; (ii) self-reports of the lived experience; and (iii) proxy indicators. Whereas Deller (2018) and Tirado Herrero (2017) caution against focusing excessively on a single EP metric/definition, Thomson et al. (2016) highlight the appeal of headline statistics to galvanise political action; Thomson et al. (2017) and Tirado Herrero (2017) provide overviews of alternative EP measurement approaches in the European context. A range of other papers use panel data to explore the dynamics of energy poverty, including Roberts et al. (2015), Phimister et al. (2015), Chaton and Lacroix (2018) Alem and Demeke (2020) and Poggi and Florio (2010).

Other studies utilising panel data to address the relationship of EP to other factors include: Awaworyi Churchill and Smyth (2020) who consider ethnicity as a determinant of EP in Australia; Awaworyi Churchill et al. (2020) assess the impact of EP on overall life satisfaction in Australia; Charlier and Kahouli (2019) report that households in EP have a high price elasticity demand for energy; and Llorca et al. (2020) consider the link between EP and self-reported health in Spain. This connection of EP with adverse health effects follows a strand of academic and policy discussions since early papers such as Bradshaw and Hutton (1983), and more recently Liddell and Morris (2010), Sovacool (2015), Burlinson et al. (2018) and Jessel et al. (2019). Like the current paper, Awaworyi Churchill and Smyth (2020) find that the statistical significance and magnitude of the association between EP and a crucial variable (in their case ethnicity) varies according to which of three EP indicators is used, mirroring the message of the current paper. A related stream of research has addressed the issues of EP in developing countries, as part of a wider debate about development, poverty and access to energy sources, as for example in Banerjee et al. (2021), where composite indices reflect an EP country-wide measure rather than household-level characteristics.

The dataset used in this study, and described in more detail below, enables a more comprehensive and detailed assessment of how perception- and expenditure-based EP indicators overlap, both confirming previous findings and enabling nuances to be identified and extended. The time period covered (2001-2 to 2008-9) includes periods of some energy price fluctuations, so that we can confirm that the lack of overlap between EP indicators is persistent through time, rather than a temporary phenomenon. Moreover, the paper provides the first analysis of IAAW EP using the BHPS. The more recent Understanding Society dataset does not contain a question specifically asking about the affordability of warmth, and so directly equivalent analysis for the UK cannot be extended to more recent years. However as we show below, later data confirm the continued general applicability and relevance of the findings.

3. Data and Methodology

The BHPS is an annual survey conducted between 1991 and 2009[7]. The first survey wave was designed as a nationally representative sample of private households in Great Britain and involved 5,500 households. To allow analysis of the devolved administrations, two ‘booster’ samples of 1,500 households were added, covering Scotland and Wales respectively in 1999; two years later the sample was further enhanced by a further 2,000 households from Northern Ireland. The survey added households which evolved from the initial set of households[8], as well as the original interviewees, where possible. To simplify the interpretation of results, especially regarding time trends and geographic identifiers, our analysis begins in 2001-02 to coincide with the introduction of the Northern Ireland booster sample.

Inclusion of the booster samples results in oversampling of households from the devolved administrations, and increases the number of self-reports of EP. Households in the devolved administrations are at greater risk of EP due to a combination of lower average incomes (Wales and Northern Ireland) and a less extensive gas grid and cooler temperatures (Scotland and Northern Ireland) than in England. We analyse this unrepresentative survey to obtain the best understanding of how the EP indicators differ, rather than to provide population estimates of the prevalence of EP.

To be included in the analysis a household must provide complete data for all the relevant explanatory variables, including those needed to calculate the three EP indicators, in at least one survey wave[9]. Applying these criteria resulted in 55,772 observations from 10,465 households in an unbalanced panel from 2001-02 to 2008-09.

The two expenditure-based indicators (10% EP and LIHC EP) mirror England’s official fuel poverty statistics[10] used between 2001 and 2012, and between 2012 and 2021 respectively. However, as noted above, the expenditure-based indicators calculated here differ from the official English statistics in two ways, namely their use of reported rather than modelled ENEX, and gross income rather than income net of taxes[11]. The official statistics estimate the ENEX needed to achieve 21°C in the primary living area, according to an engineering model, but this modelled ENEX variable is not available for our comparative exercise[12]. Modelled ENEX has advantages over reported ENEX because the latter may under-record EP if the poorest households restrict their ENEX[13]. However, Deller and Waddams Price (2017) suggest it is simplistic to assume such under-recording is universal, since in some time periods EP rates in England based on reported

[7] Our data are taken from the survey, and so depend on its sampling basis.
[8] For example, when an adult child moved out.
[9] Households where annual ENEX as a proportion of annual household income was zero or exceeded 100% were dropped, due to the high probability of measurement error.
[10] Appendix 1.1 provides definitions for the official indicators.
[11] Matching the official income definition, gross income in our calculation is inclusive of benefits. Gross income is used as it is an official variable in the BHPS, whereas only an ‘unofficial’ net income variable can be obtained.
[12] The BHPS does not include modelled ENEX as a variable, while the English Housing Survey’s EP dataset does not include the necessary perception-based EP indicator. See the variable list in BEIS (2017).
[13] See Hills (2012), Liddell et al. (2012) and Thomson et al (2017).

ENEX are higher than those based on modelled ENEX. Moreover use of recorded (rather than modelled) expenditure has some advantages, since it is closer to the lived experience of individual households (for example, Summerfield et al., 2019, notes systematic discrepancies between the actual gas consumption of older larger dwellings in the UK and model predictions).

The perception-based indicator (IAAW) is derived from a question asked only of households who first reported an inability to keep their home adequately warm. It thus omits households who struggle to afford their energy, but feel that nevertheless they can manage to heat the home adequately. This measure seemed a clearer indicator that the household struggled to afford adequate warmth than inability to keep adequately warm, which does not include an affordability component. Similarly, we considered that reporting 'Inadequate heating facilities' lacked the necessary affordability element and so was an unsuitable metric. Figure 4 in Appendix 2 explores the overlap between IAAW and these two other related responses.

When exploring the household characteristics associated with each EP indicator we focus on the main exogenous features: age of the household head (under 65, 65-75 or over 75); whether the household contains children; the number of household members; whether the household has a piped gas connection; and the UK nation (devolved administration) where a household is located.[14] The relationship between IAAW and three additional variables, namely gross annual household income, annual reported ENEX and annual housing costs (net of housing benefit), is also explored, though, as explained below, it is not meaningful or helpful to explore a similar relationship with the expenditure-based measures. All monetary amounts are converted to 2008 prices using the Consumer Price Index. As a control, survey wave dummies and month dummies, reflecting the year and season when the survey was administered, are included in the regressions.

Logit models are used to identify the associations of the household characteristics mentioned above with each EP indicator when controlling for other factors and time dummies. The dependent variable, y_{it}, takes a value of 1 when household *i* is energy poor in period *t* and a value of 0 when a household is not energy poor. For each household the probability, p_{it}, of being energy poor in period *t* can be expressed as:

$$y_{it} = \begin{Bmatrix} 1\ with\ probability\ p_{it} \\ 0\ with\ probability\ 1 - p_{it} \end{Bmatrix} \quad (1)$$

where the probability of being energy poor, p_{it}, is modelled as:

$$p_{it} = Prob(y_{it} = 1|\boldsymbol{x_{it}}) = F(\boldsymbol{x_{it}}'\boldsymbol{\gamma}) \quad (2)$$

Here p_{it} is the probability that household *i* is energy poor in period *t* given the vector of potentially time varying explanatory variables for household *i*, $\boldsymbol{x_{it}}$. This probability can be expressed as a

[14] Additional regressions were run including the following variables: a comprehensive set of dwelling characteristics, a comprehensive set of socio-economic indicators, a comprehensive set of electrical appliance indicators, self-reported indicators of affordability issues and self-reported indicators of housing condition problems. We do not report the regressions including these additional variables due to concerns about their potential endogeneity, although they are available from the authors on request.

function of $\boldsymbol{x_{it}}$ multiplied by the regression coefficients, $\boldsymbol{\gamma}$. The logit model assumes the error process for the latent variable behind the model is logistically distributed and $F(.)$ is the logistic cumulative distribution function. To avoid problems of endogeneity, a parsimonious model with a small number of independent variables is estimated using maximum likelihood estimation following a pooled cross-section approach. As the error terms for each household are likely correlated through time, cluster robust standard errors are used, where each household, *i*, is treated as a separate cluster.

Average marginal effects are reported showing the average percentage point increase in the probability of a household being energy poor associated with a change in a particular 'explanatory' variable. Our main interest is in how different variables are broadly associated with each of the EP measures, and particularly which variables are positively related to one measure but negatively to another; and those which have a positive or negative relationship with one EP measure, but no significant relationship with others.

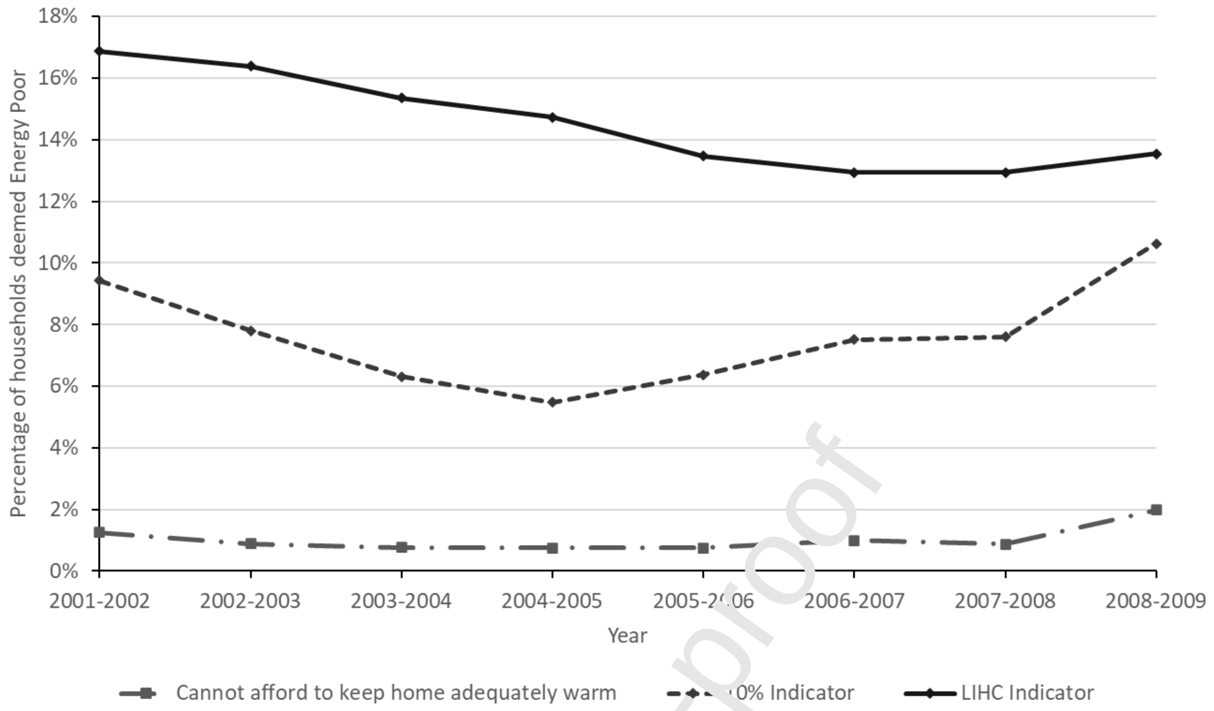
Since the 10% and LIHC indicators are calculated from gross household income (inclusive of benefits), ENEX and, for the LIHC indicator, housing costs, these three variables are not included as explanatory variables in the regressions (Table 3) for any of the indicators. However, their relationship with IAAW is shown in Table 1, alongside the univariate relationships between IAAW and each of the two expenditure-based indicators. Table 1 also reports the effect of being categorised as IAAW in one time period on the likelihood of being similarly classified in the following time period; lags are not included in the main regressions since these would mask the influence of variables which vary little over time

4. Relationships between Energy Poverty indicators

4.1 Differences in the incidence of Energy Poverty

Figure 1 shows large differences in the percentage of households which report IAAW and those identified as being in 10% or LIHC EP within the sampled households. No more that 2% report IAAW EP in a given year, while in each year more than 5% of households are energy poor according to the 10% indicator, and more than 12.9% according to the LIHC indicator. Our use of panel data across several years confirms that while all the measures follow some similar patterns (such as the upturn in the final observations) the differences between them are persistent and evident in each wave of interviews. This includes times of both stable (2001- 2004) and rising energy prices (from 2005).

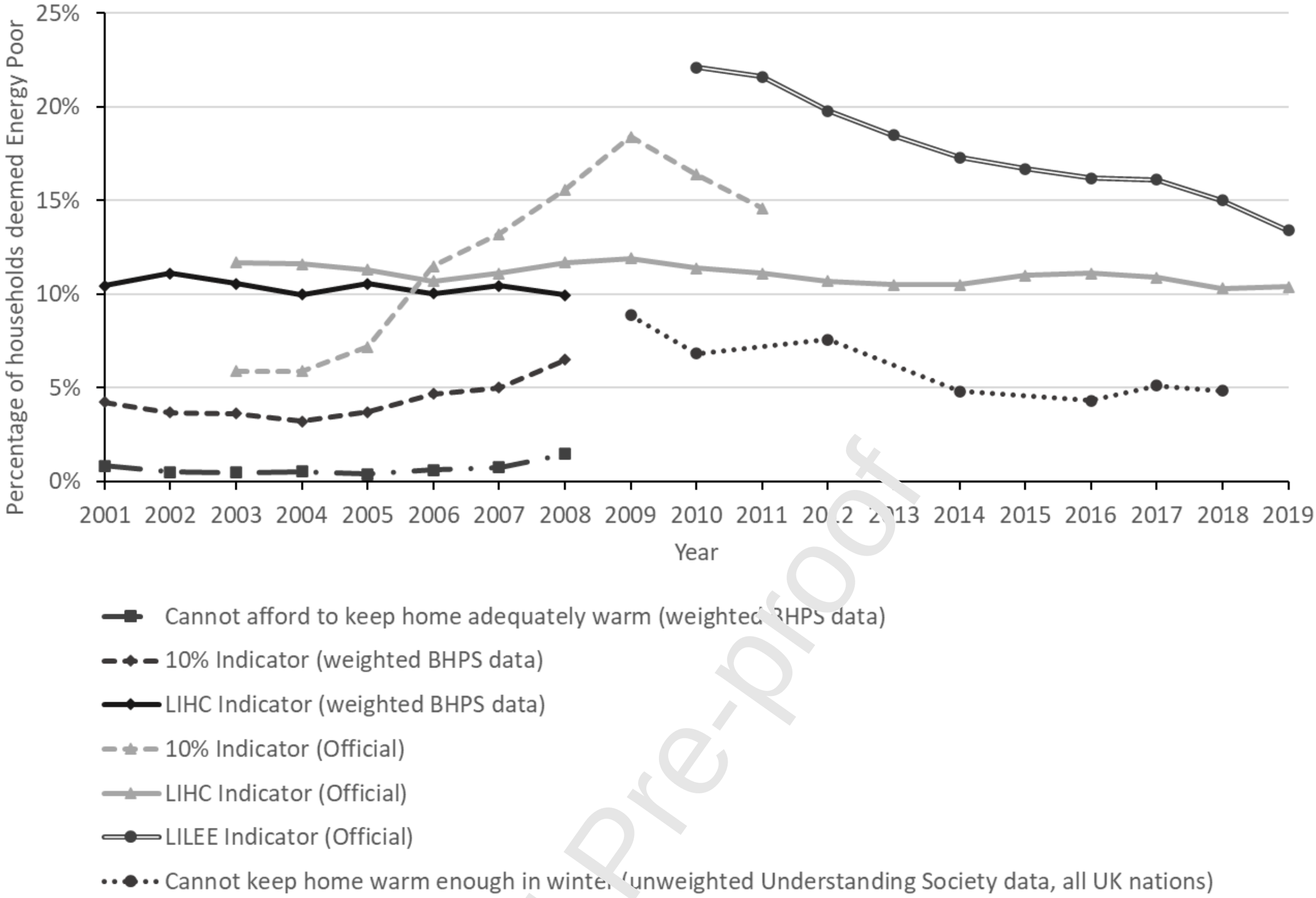
Figure 1 : Rates of EP, alternative indicators, 2001-02 to 2008-09 (unweighted)



[two-column fitting image]

The sharp increases in energy prices from 2005 are associated with growth of the sample median ENEX at five times that of median income, and the 10% indicator reflects this increase in the share of household expenditure devoted to energy (Deller and Waddams Price, 2018, Figure 5 p. 25). The effects of the price and energy share increases are somewhat absorbed in LIHC by its relative nature; this measure's more persistent downward trend is also influenced by the oversampling of households in the devolved administrations, where median incomes within our overall sample grew almost twice as fast as in England between 2001-02 and 2008-09.

Figure 2: Estimates of EP indicators from BHPS data and official statistics[15] for England



[two-column fitting image]

To compare our estimates with official and more recent data, Figure 2 presents the corresponding estimates in Figure 1 for England alone, alongside the official 10% and LIHC statistics. Our indicators show similar patterns to the official figures but lie consistently below them. For the LIHC indicator, the use of gross rather than net income in calculating our statistics is the most likely explanation for this difference. For the 10% indicator, the gap between our indicators and the official statistics increases markedly over time. This growth in the difference can be explained by the rising energy prices: the official 10% indicator uses modelled ENEX, which holds energy consumption fixed at the 'ideal' level; while our 10% indicator uses reported ENEX which would reflect any reduction in energy consumption from households responding to higher costs. We note that using the official statistics would suggest an even *greater* difference between the levels of the IAAW and the expenditure-based indicators, further emphasising the challenges of using any single one of the official indicators. The 'cannot keep home warm enough in winter' question from

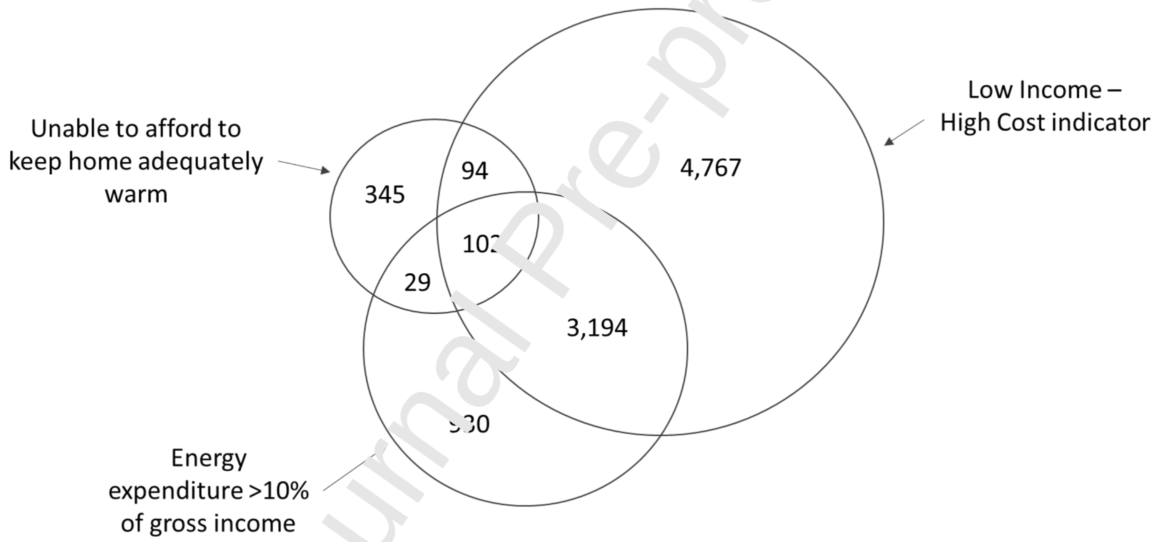
[15] Data for the official energy (fuel) poverty statistics for England run from 2003 onwards. The official LIHC statistics are from: Table 1, Trends in Fuel Poverty, England 2020 (2003 to 2018 data), https://www.gov.uk/government/statistics/fuel-poverty-trends-2020 (accessed on 8 January 2021). The official 10% statistics are from: Table 1a, Long-term trends under the 10 per cent measure, https://www.gov.uk/government/statistics/trends-in-fuel-poverty-england-2003-to-2011 (accessed on 8 January 2021). Where the year is marked as '2003-2004' in the graph, the official statistics refer to 2003, and for 2004-2005 the official statistics refer to 2005 etc.

the Understanding Society data is the closest to IAAW, but, as shown, is asked only in some waves. Its one step approach and more general nature, omitting specific reference to affordability, explain why it is at a higher than IAAW, but it remains well below the other official measures. There are no equivalent official comparators for the IAAW indicator.

4.2 Overlap between Energy Poverty indicators

Figure 3, based on pooled data from 2001-02 to 2008-09, depicts the limited overlap between the different EP indicators estimated from the BHPS. Amongst the observations classified as EP according to at least one of the EP indicators, only 1.1% involved a household reporting all three indicators simultaneously in a particular year. Figure 3 also illustrates the asymmetric overlap between the two expenditure-based indicators: while 77% of observations of 10% EP involved a household that was also LIHC EP, only 40% of observations of LIHC EP were simultaneously categorised as 10% EP.

Figure 3: Overlap between EP indicators, observation nos. (areas not to scale)



[two-column fitting image]

This minimal overlap between expenditure-based EP and IAAW occurs in each time period, though the intersection is higher at the beginning and end of the period studied (see Figures 6 and 7 in Appendix 2). Although the proportion of 10% EP households reporting IAAW rose from 2.1% to 4.8% between 2007-08 and 2008-09, coinciding with energy prices rises, the overlap between EP indicators in 2008-09 remains low. In none of the years studied does the proportion of 10% or LIHC EP households reporting IAAW exceed 5%. This stark comparison implies that at least 95% of households identified as EP by either of the official-related metrics believe that they can afford to keep warm (though we note that the structure of the questions limit their numbers to some extent). Similarly at least 60% (70%) of those who indicate that they cannot afford adequate warmth are not classified as EP by the LIHC (10%) indicator.

Despite such limited overlap, in each year households who are energy poor by one of the expenditure-based indicators are more than twice as likely to report IAAW as the overall sample.

Similarly, households reporting IAAW are more likely to be expenditure energy poor, especially according to the LIHC indicator. These small but statistically significant overlaps are reflected in the Pearson correlation coefficients between the EP indicators. All are significantly different from zero at the 1% level, but their values range from 0.511 (between the 10% and LIHC indicators) to less than 0.06 between IAAW and each of the expenditure-based indicators (see Table 4 in Appendix 2). Table 1 reflects this relationship between the measures through the small (though statistically significant at the 1% level) average marginal effects of each of the expenditure EP indicators on the probability of reporting the IAAW indicator (columns 1 and 2).

Table 1: Average marginal effects of other EP indicators, income and energy expenditure on the probability of reporting IAAW

Explanatory Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1. Classified as 10% energy poor	0.022***						
2. Cassified as LIHC energy poor		0.016***					
3. Energy expenditure share (%) - quadratic[1]			0.001***				
4. Annual energy expenditure (£ hundreds, 2008) - quadratic[1]				-0.000		0.000***	0.000***
5. Gross annual household income (£ thousands, 2008) - quadratic[1]					-0.001***	-0.001***	-0.000***
6. Annual net housing costs (£hundreds, 2008) - quadratic[1]							0.000***
7. Reports IAAW, period t-1							0.231***
Log likelihood	-3,113.96	-3,109.59	-3,067.88	-3,179.29	-3,018.51	-3,009.61	-2,103.10
P-value, likelihood ratio test of joint significance	0.000	0.000	0.000	0.678	0.000	0.000	0.000
Number of observations	55,772	55,772	55,772	55,772	55,772	55,772	47,973
Number of households	10,465	10,465	10,465	10,465	10,465	10,465	9,400

Notes: * indicates statistical significance at the 10% level, ** indicates significance at the 5% level and *** indicates significance at the 1% level. The table reports average marginal effects on the probability of a household reporting an inability to afford to keep their home adequately warm. A blank space indicates a variable was not included in a regression. The base category for row 1 is not being 10% energy poor, for row 2 it is not being LIHC energy poor and for row 7 it is being able to afford adequate warmth in period t-1. In column (7) 8,279 observations were dropped as the sample is restricted to cases where the lag of IAAW is available. In some regressions some observations where households reported they could afford adequate warmth were completely determined. In column (5) 10 observations were completely determined, in (6) it was 12 observations and in (7) it was 22 observations.

[1] Where a variable is labelled as quadratic the regression included both a linear and squared term of the variable; the reported average marginal effect is the combined change in probability associated with the linear and squared terms.

Table 1 also shows the relationship between the IAAW indicator and the underlying elements which generate the binary 10% and LIHC indicators, namely income and ENEX. Figures 8 to 10 in Appendix 2 confirm that the relationships between ENEX, ENEXShr (the share of household income devoted to ENEX), income and IAAW are non-linear, and so the variables ENEXShr, ENEX and income are each included in quadratic form. While the relationship between ENEX and IAAW is not statistically significant at the 10% level when ENEX is included as the sole independent variable (column 4), there is a statistically significant positive relationship between ENEXShr and IAAW (column 3) and a negative relationship between household income and IAAW (column 5).

Columns 6 and 7 show the associations with IAAW when both ENEX and income are included in the regression as separate quadratic variables, rather than as ENEXShr. Wald tests reject the hypothesis that the coefficients on income and ENEX are the inverse of each other (when used separately as absolute values in column 6) confirming that they should be included as separate variables rather than combined as ENEXShr. Columns 6 and 7 indicate a statistically significant relationship between IAAW and ENEX, once household income is controlled for, though the magnitude of the relationship remains small. For example, a £1,000 increase in household income is associated with a 0.1 percentage point drop in the probability of IAAW, while a £100 increase in ENEX is associated with a less than 0.05 percentage point increase in the probability of IAAW (column 6). For ENEX it is the coefficient of the linear element which is statistically significant, confirming that the magnitude of the average marginal effect is genuinely small rather than an average of negative and positive effects.

Column 7 shows the effect of including annual net housing costs (these constitute the third component of the LIHC indicator) and the first lag of IAAW as explanatory variables. After controlling for ENEX, income and the first lag of IAAW, there is a positive non-linear relationship, with a very small magnitude, between net housing costs and IAAW. Similarly, when ENEX, income and net housing costs are controlled for, column 7 also demonstrates that being IAAW energy poor in the previous year increases the chances of being so in the current year by 23 percentage points. While this indicates an important determinant of IAAW in any one year, this lagged variable is excluded from the multivariate analysis below since it would mask associations with other variables which vary little over time.

In its confirmation of the statistically significant but small associations between IAAW and the binary 10% and LIHC EP indicators, as well as with the underlying continuous variables which generate the expenditure-based EP indicators, table 1 confirms similar findings in previous studies. Waddams Price et al. (2012) find a somewhat greater coincidence between 10% EP and feeling unable to afford energy, reflecting both a different perception-based measure of affordability and the low income sample of that study. Using data from the English Housing Survey, BEIS (2020) finds that only 10% of LIHC energy poor households felt unable to keep their home comfortably warm, while only 19% of households who felt unable to keep their home comfortably warm were LIHC energy poor. Other papers provide similar comparisons between perception- and expenditure- based indicators, but different EP definitions make direct comparisons of results difficult. For example, Agbim et al. (2020) identify households spending above 8% of income on electricity for Texan households as "objectively energy burdened", while also considering whether households had difficulty paying their electricity bill. This broader perception-based indicator resulted in an EP rate (34%) higher than that classified by their expenditure-based indicator (23%). The limited overlap between 10% EP and being unable to afford warmth mirrors Palmer et al.'s (2008)[16] findings which use modelled ENEX, and so are independent of our use of reported rather than modelled expenditure.

Dubois (2012), Boardman (2011) and Tirado Herrero (2017) attribute low rates of perception-based EP compared with expenditure-based EP to households being unable or unwilling to self-identify as energy poor. One possible explanation for the discrepancy between the expenditure-

[16] Palmer et al. (2008) report that only 6% of those identified as 10% energy poor stated that their living room was not kept comfortably warm in winter and that the reason for this was cost.

and perception-based EP indicators is that the thresholds of the expenditure-based EP indicators may not reflect where the majority of householders consider energy to become unaffordable. The boundary may be elsewhere, or householders may view energy affordability as a spectrum rather than a binary 'Yes/No' situation as posed in the BHPS question. Neither of the expenditure-based definitions explicitly assessed *householders'* (rather than commentators') opinions of an unaffordable level of income devoted to ENEX. Alternatively, householders may view energy as a necessity and so choose to spend a high proportion of their income on energy to ensure adequate warmth; as noted above, if a household does not report inadequate warmth, they would not have been asked the affordability question. In this case the main impact of high ENEX might be to restrict the consumption of other goods.

On the other hand, a household reporting IAAW, but devoting a low proportion of income to ENEX, may be restricting their energy consumption for affordability reasons. This is the disadvantage of using reported actual expenditure, rather than what may be modelled as desirable, since such energy rationing is not observed. To identify whether there is a problem, and how best to address it, information is needed both on the temperatures to which householders aspire and those that are achieved in the home. Some households may have inadequate information about the health benefits of different ambient temperatures; some may be pursuing a particular temperature level because of medical conditions or personal preference, others may live in energy inefficient homes or not have access to the cheapest available energy; some may be rationing energy and/or other goods because of low income, while other relatively well-off households may have a preference for particularly high (or low) temperatures. We argue for the importance of collecting new data which specify temperature preferences and realisations for individual households, to identify the nature of any problem and how best to address it.

4.3 Characteristics of households by Energy Poverty indicator

Table 2 provides an initial description of the characteristics of households in each EP classification. As expected, each category of energy poor households has lower average incomes than the sample as a whole: the 10% EP group has a particularly low median income of £7,483, only 57% of the median income of IAAW households. Households who are energy poor according to the expenditure-based indicators also spend more on average on energy (ENEX) than the whole sample, with households classified as 10% energy poor showing the highest median ENEX and ENEXShr. In contrast, the median ENEX for IAAW households is close to the average across the sample, although the median ENEXShr for this group is above that for the whole sample, suggesting that IAAW does not necessarily identify households who are 'rationing' their energy consumption. Nevertheless, the ENEX of IAAW households might still reflect constrained in-home temperatures if their dwelling characteristics and/or average energy price mean they obtain less heat for a given quantity of ENEX than do other households.

The most noticeable difference in other characteristics concerns the age of the head of household. Within the sample those identified as energy poor by the 10% and LIHC indicators involve a greater proportion of households with a head aged 65 or over compared to the sample as a whole, whereas IAAW households have a lower proportion of older household heads. This contrast is even more marked for households with a head aged over 75. All three EP indicators align in including a greater proportion of households in Northern Ireland, and of those who lack a gas connection, than the average for the sample.

Table 2: Characteristics of households classified as EP according to each indicator

Household Characteristic	Whole sample	Energy Poverty Indicator: Inability to Afford Adequate Warmth	Energy Poverty Indicator: 10% indicator	Energy Poverty Indicator: LIHC indicator
Median gross household income (£, 2008 prices)	25,499	13,714	7,483	11,550
Median energy expenditure (£, 2008 prices)	797	776	1,124	1,033
Median energy expenditure share (%)	3.2	5.9	13.6	8.9
Median net housing cost (£, 2008 prices)	2,042	678	0	173
% with household head aged 65-75	13.2	10.2	17.2	14.8
% with household head aged 75+	12.2	7.0	19.9	14.9
% containing children	31.6	27.5	23.1	39.3
Mean number of household members	2.5	2.1	1.9	2.6
% with no gas connection	25.1	42.6	42.4	35.9
% in Northern Ireland	18.6	27.2	43.1	33.6
% in Scotland	18.9	20.0	18.0	20.2
% in Wales	16.8	19.6	14.8	17.1
Number of observations	55,772	570	4,255	8,157
Number of households	10,465	380	2,192	3,547

Note: All percentages and averages use the number of observations (for the relevant group) as the denominator.

We extend the descriptive analysis above to explore the associations of the main exogenous household characteristics with each of the three EP indicators, while controlling both for the year and month of each household observation and for the other variables included in the multivariate regressions.

Table 3: Average marginal effects on probability of being identified as EP, by indicator

	EP indicator		
	IAAW	10%	LIHC
	(1)	(2)	(3)
1. Household head aged 65 to 75	-0.006***	0.012**	0.045***
2. Household head aged 75+	-0.009***	0.019***	0.057***
3. Contains children	0.004	0.085***	0.112***
4. Number of household members: 2	-0.014***	-0.114***	-0.048***
5. Number of household members: 3	-0.014***	-0.156***	-0.071***
6. Number of household members: 4	-0.018***	-0.170***	-0.087***
7. Number of household members: 5	-0.016***	-0.168***	-0.062***
8. Number of household members: 6	-0.017***	-0.179***	0.006
9. Number of household members: 7+	-0.017***	-0.164***	0.116***
10. No gas connection	0.008***	0.008*	0.018***
11. Wales	0.005***	0.027***	0.055***
12. Scotland	0.003	0.026***	0.062***
13. Northern Ireland	0.003	0.113***	0.148***
Log likelihood	-3,036.41	-13,192.71	-21,869.02
P-value, likelihood ratio test of joint significance	0.000	0.000	0.000
Number of observations	55,767	55,767	55,767
Number of households	10,465	10,465	10,465

Notes: * indicates statistical significance at the 10% level, ** indicates significance at the 5% level and *** indicates significance at the 1% level. The table reports average marginal effects on the probability of a household being classified as energy poor. Base categories: rows 1 and 2 = Household head aged less than 65; rows 4-7 = household contains 1 person; row 10 = having a gas connection; and rows 11-13 = England. All regressions also include survey wave and interview month dummies. In all columns 5 observations were dropped for May perfectly predicting energy poverty.

Table 3 confirms the strikingly different associations with age of each indicator, verifying the descriptive statistics of Table 2 and confirming results from other studies. While the expenditure-based indicators are each positively associated with an older head of household, age is negatively associated with the IAAW measure. If the LIHC measure is used, a household with a head over 65 years old is 4.5 percentage points more likely to be classified as Energy Poor than a younger household; while the equivalent figure for the 10% measure of Energy Poverty is 1.2 percentage points. In contrast, the IAAW metric indicates a 0.6 percentage point *reduction* in the probability of EP for such households. These differences are even more marked for households with a head over 75 years old. These disparities clearly point in very different policy directions according to the measure chosen, and illustrate the influence and importance of the choice of EP indicator.

While the differences between the measures are most striking in their association with age of household head, associations between EP and other household characteristics also vary according to the EP metric chosen, in particular between the expenditure-based indicators and self reported affordability. A household including children is 11.2 (8.5) percentage points more likely to be in LIHC (10%) EP, but no more likely to report an IAAW. The different associations with large households (positive for LIHC but negative for IAAW and 10%) are probably a technical consequence of equivalisation adjustments[17]. Not having a gas connection increases the risk of EP according to all three metrics. Camboni et al. (2021) find a similar relationship in Italy in much more recent data.

In terms of the devolved administrations, the expenditure-based measures have a positive association with location in Scotland or Northern Ireland (compared with England). Residence in Northern Ireland is associated with a 14.8 percentage point increase in the likelihood of being Energy Poor according to the LIHC measure (11.3 percentage points for the 10% indicator); there are similar (but smaller) positive associations with the expenditure-based EP indicators and location in Scotland. In contrast, the IAAW metric shows no statistically significant difference in the probability of being energy poor between England, Northern Ireland and Scotland. However there is a positive association of living in Wales and all three EP measures, though with different average marginal effects for each.

These relationships are present even after taking account of changes from year to year, and of the month in which households were interviewed. Monthly dummies show that higher levels of the 10% indicator are associated with reporting in the winter months, when fuel expenditure, which partly defines the measure, is likely to be higher. Although invited to calculate their annual energy expenditure, households' estimates may be influenced by their most recent bills. Households interviewed in these months may also differ in other ways from those who report in the autumn, since a later interview date implies failure to interview the household earlier in the cycle. The annual changes, including differences between the indicators, confirm the trends over time illustrated in Figure 1 above. After discussing the robustness of these findings, in section 6 we discuss their implications both for comparative academic analysis and for targeting policy to reduce Energy Poverty.

5. Robustness

A number of tests have been performed to confirm the robustness of the results in Table 3. First, the risk of multicollinearity among the explanatory variables was checked by calculating the variance inflation factor (VIF) for all variables. The VIFs obtained had a mean of 1.42 and a maximum value of 2.14, indicating that multicollinearity is not a significant issue in our model.

The regressions in Table 3 have also been re-run using probit and cloglog link functions. As is common, there is generally very little difference in the log likelihoods when the different link functions are used. Using the logit function gives the highest (least negative) log likelihood for all but one of the regressions. For the IAAW indicator, the cloglog link function has a log likelihood which is less than 0.01% higher; unsurprisingly, given the small size of this difference, using the cloglog link function does not change the magnitude or significance of the explanatory variables in column 1 of Table 3.

[17] Equivalisation reflects that the same income divided among a larger number of household members will result in a lower standard of living. The equivalisation methodology is detailed in DECC/BRE (2016).

Since panel data are being used, another potential concern is whether the results are affected by attrition attributable to unobservable characteristics; because our main aim is to compare differences in the associations across the three EP indicators, we focus on any differences in the attrition rates between the indicators. The attrition rates across the indicators are reassuringly similar. Averaging across all analysed survey waves, a household reporting IAAW in one period has a probability of 0.186 of not having all the required data in the following period, compared to a figure of 0.180 for the 10% metric and 0.163 for the LIHC metric.

For the regressions in Table 3 the variables have been carefully selected to minimise the risk of endogeneity. Equivalent regressions have also been undertaken with a far larger set of explanatory variables as detailed in footnote 15, but we do not report these regressions due to concerns that these additional explanatory variables could be endogenous, leading to potential inconsistency and bias in the estimated relationships. While any results from these additional unreported regressions should therefore be treated with caution, and the individual marginal effects can change substantially with the inclusion of the additional variables, the core qualitative result that different indicators identify EP in different types of household remains clear.

By performing pooled cross-sectional analysis we maximise the available data to identify associations between EP indicators and different explanatory variables. The pattern of associations across the three EP measures might differ if only a single year of data were available for analysis, due to the much smaller sample size. For example, we have noted a positive relationship (significant at the 5% level) between a household head being aged 65 to 75 and being 10% EP (Table 3, column 2); while if equivalent regressions are performed separately for each year, an equivalent statistically significant positive relationship is identified only in the 2008-2009 wave.

6. Conclusions and Implications

The associations shown in Table 3 do not indicate causality; for example, moving a household from one region to another would not necessarily imply a change in its EP status. However understanding the differences between the metrics and what they are measuring is important to provide a consistent base for academic studies, both to assess changes in the prevalence of EP over time and to compare EP in different places and regions. Such comparisons can elucidate the nature of home temperature issues in different climates, areas and circumstances of economic development, as the burgeoning literature in different types of economy and the papers cited in section 2 above have shown. Associating each EP measure with specific household characteristics both identifies those at risk and indicates potential routes to deliver effective policies. Our analysis illustrates the methodological issues which lie behind the estimation of EP, and how different metrics reveal the complex nature of the underlying phenomenon of inadequate household temperature control. Although the data relate to a specific regime and do not enable very recent comparisons, their analysis confirms and illustrate these general lessons.

EP has been a particularly salient policy issue because of its continuing prevalence among low-income households. Moreover strategies to introduce low carbon energy will introduce new costs, for example from the stranded assets of boilers and systems designed for carbon based fuels and from reconfigured distribution systems. Such additional costs are likely to change the balance of prices for different households according to their energy usage and assets, posing new challenges for energy affordability. Some policies may aim to improve both EP and environmental concerns, and many past campaigns have focused on improving home energy efficiency.

Much discussion has centred around identifying a single 'best', perhaps composite, measure of EP. The analysis in this paper confirms the clear differences and lack of overlap between commonly used and advocated EP measures. Not only does the overall prevalence of EP vary enormously by indicator, but the types of household which are identified as vulnerable in each definition also differ considerably: many are classified as energy poor by only one indicator, and very few by all three. Policies and their effects will differ according to the indicator chosen – a very real example of 'what gets measured gets managed'. The official indicator becomes the focus of Government policy and measurement, and influences how resources are allocated to alleviate EP. Moreover the contrasts identified expose the fundamental differences in what each indicator is measuring and challenge the direction and focus of EP alleviation policies.

The differences between the household characteristics associated with the various EP measures are starkest in relation to age: households with older heads are more likely to be classified as energy poor according to the 10% and LIHC indicators but are less likely to report IAAW. This is particularly pertinent in the UK, the source of the data analysed here. The government instituted a universal Winter Fuel Payment in 1997, payable tax free to all those of pensionable age, which cost almost £2 billion in 2020-21. This formed an important plank of subsequent fuel poverty policy and of a working definition of EP based on the 10% measure from 2001. The positive association of age with the expenditure-based indicators provides some justification for this measure of fuel affordability, and for its replacement, the LIHC measure from 2012, since both are expenditure based. However, the most recent measure of EP, introduced nine years later, is based on Low Income, Low Energy Efficiency (LILEE), is independent of expenditure: official data show lower incidence of EP amongst older households than among the population as a whole in each year from 2010 to 2019 (Department for Business Energy and Industrial Strategy, 2021). Removing the expenditure focus inverts the association of older households with EP; a self-reported affordability measure would make the contrast even starker, as the analysis here shows. The argument for a universal age-related benefit is much weaker if EP is measured by LILEE or IAAW. This example shows how the choice of a particular indicator directly influences the arguments for support to particular households.

Focusing on any single EP indicator inevitably excludes households whose characteristics might make them attractive targets for alleviation policies under alternative measures, as Figure 3 illustrates. Each indicator reveals a particular aspect of EP, but each also has limitations. In particular, some official expenditure-based indicators rely on engineering models of the costs of achieving pre-specified levels of temperatures, rather than assessing those actually achieved in a home, let alone relating them to the households' own preferences. Specifying a single superior EP indicator, either by choosing one of those discussed here or by constructing some composite indicator, risks losing much of the richness and nuance of households' experience which influences each measure. Rather than discarding the information incorporated in each of these measures, we recommend supplementing it with direct measurement of in-home temperatures and evidence on householders' own temperature preferences.

There have been few recent large-scale attempts[18] to measure the temperatures achieved in different homes in the UK, despite Hills' (2012) recommendation. However such large-scale temperature measurements have become more feasible with new technologies and the roll-out of smart thermostats, which provide a valuable opportunity for a more direct policy approach to EP. For example, in the UK over 1.5 million households have the British Gas Hive system[19]. Although early adopters of smart thermostats may have relatively high incomes, and so be at low risk of EP, systems specifically targeted at social housing[20] may prove particularly relevant to understanding EP. This might build on Gouveia et al. (2018)'s use of smart meter data in a Southern European context, though we recommend assessing achieved temperatures against householder preferences, rather than using building based energy simulations as in that study.

Temperature data would enable both improved understanding, assessment, policy targeting and policy evaluation through more direct information on the phenomenon and on the benefits which each household obtains from energy consumption. Without direct measurement of warmth and preferences, each of the current EP indicators risks errors both of inclusion and exclusion, and potentially distorted understanding and policies regarding the prevalence and nature of homes that are too cold or too warm. Policy based on combining the data from current EP indicators with information on temperatures and temperature preferences is more likely to succeed in addressing the fundamental challenges of cold homes or excessive heat.

Funding

This work was supported by the UK Energy Research Centre Phase 3, Grant Ref: EP/L024756/1 as part of the 'Equity and Justice in Energy Markets' project. The funding was granted after a proposal providing a broad outline of the research was submitted; beyond approving this proposal, the funder had no role in the conduct of the research.

[18] Huebner et al. (2019) and Oreszczyn et al. (2006) use data on 823 and 1064 households respectively

[19] See https://www.britishgas.co.uk/smart-home/hive-heating.html (accessed on 8 January 2021).

[20] Such as Switchee in the UK, see 'Affordable housing industry switching on to Switchee's innovative data tools', CITY A.M., Tuesday 21 April 2020, available at: https://www.cityam.com/affordable-housing-industry-switching-on-to-switchees-innovative-data-tools/ (accessed on 8 January 2021).

Acknowledgements

The constructive comments of CCP's 'Equity and Justice in Energy Markets' project team and seminar participants at the Centre for Competition Policy are gratefully acknowledged, including Farasat Bokhari, Steve Davies, Ruth Hancock, Kai Uwe Kuhn, Franco Mariuzzo and Georgios Papadopoulos.

8. Appendices

Appendix 1 - Energy Poverty indicators

A1.1 Official fuel poverty definitions

DECC/BRE (2016) describes the official English fuel poverty statistics' methodology.

10% metric A household is fuel poor if the value of the following ratio exceeds 0.1:

$$FP\ Ratio = \frac{Required\ Fuel\ Costs}{Income}$$

Income is net of tax and benefits.

LIHC metric This definition involves two thresholds, a household is fuel poor if both:
1. Required fuel costs are above the national median
AND
2. Income remaining *after* the deduction of required fuel costs is below the official poverty line.

Income is income after taxes and benefits as well as the deduction of housing costs and equivalisation, where housing costs are restricted to mortgage and rent payments (net of housing benefits). The official poverty line is defined as 60% of median equivalised disposable income[21]. When calculating the LIHC metric, required fuel costs are also equivalised using a different equivalisation factor.

LILEE metric This definition combines the second of the thresholds above with one based on the energy efficiency of their home. A household is considered to be fuel poor if both:
1.They are living in a property with a fuel poverty energy efficiency rating of band D or below
AND
2. When they spend the required amount to heat their home, they are left with a residual income below the official poverty line

The official annual fuel poverty statistics for England are based on English Housing Survey (EHS) data from two consecutive waves which combines a household interview with a physical survey for around 6,000 households. Required energy use is based on the EHS's physical survey and aggregates estimates reflecting: space heating, water heating, lights, appliances and cooking. Each of these estimates is calculated using an engineering model and a set of assumptions, for example that all households aim to heat their main living space to the same temperature.

A1.2 BHPS data for the expenditure-based indicators

The ENEX used to calculate the 10% and LIHC indicators in the present study refers to energy expenditure during the 12 months prior to interview. Four questions separately record expenditures on electricity, gas, oil and coal/other fuels. For example, the question for electricity was:
"In the last year, since September 1st 1999, approximately how much has your household spent on domestic fuel starting with…Electricity"
The expenditures on each fuel are then summed to give total annual ENEX.

[21] Equivalised after housing costs net income.

The 10% indicator is calculated by dividing total annual ENEX by gross annual household income (inclusive of benefits). Calculating the LIHC indicator is more involved, since median ENEX and the income poverty line need to be estimated for each year. Because the devolved administrations are oversampled, weights supplied with the BHPS are applied to make the median estimates representative of the population of UK households. To ensure representativeness, the medians are calculated using all households that answer the questions required to produce the LIHC indicator. This is a less restrictive requirement than for the main analysed sample, which also requires complete data for the explanatory variables used in the main regressions.

A1.3 Perception-based survey questions

To be classified as energy poor according to the IAAW indicator requires a respondent to first answer *No* to the following question:

"Here is a list of things which people might have or do. Please look at this card and tell me which things you (and your household) have or do? Keep your home adequately warm"

If a household answered *No*, they were then asked the question:

"Would you like to be able to keep your home adequately warm, but must do without because you cannot afford it?"

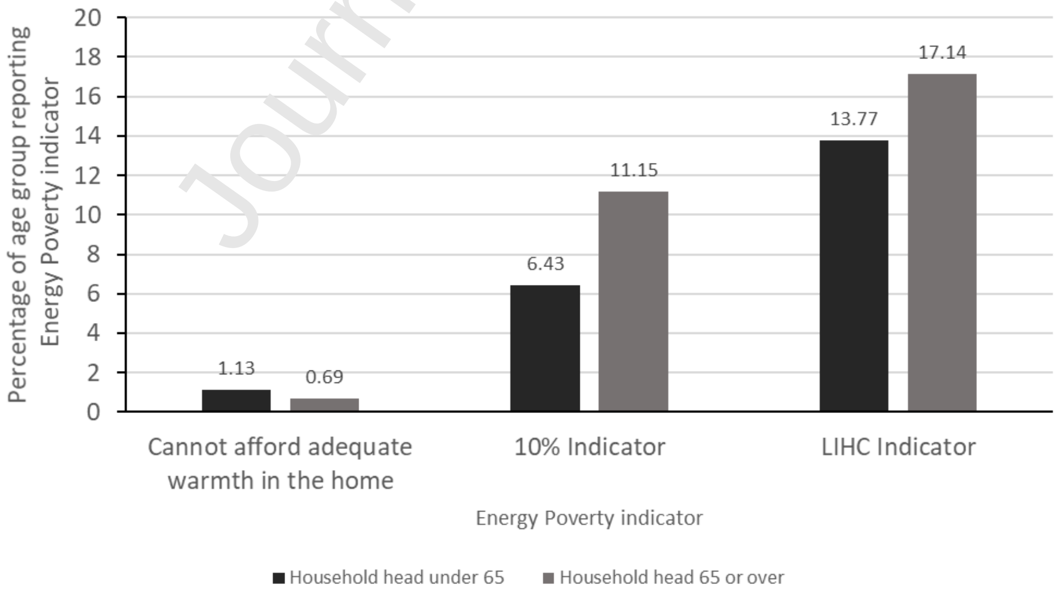
If a household responded *Yes* to this second question, they are classified as IAAW energy poor.

Appendix 2 – Additional materials

Figure 4 reports the overlap of three possible perception-based EP indicators available in the BHPS. The majority of households who felt unable to keep their home adequately warm, 71.6%, were unable to do so because they felt it was unaffordable. Nevertheless, this implies that for almost a third of households unable to keep their home adequately warm, they perceived the reason for this to be something other than affordability.

Figure 4 Overlap of potential perception-based indicators, pooled data 2001-02 to 2008-09 (number of observations, areas not to scale)

Figure 5: % of households in EP by household head age, pooled data 2001-02 to 2008-09[22]



[22] The equality of the EP rates between households with a head aged under 65 and those aged 65 and over is rejected at the 1% significance level for all three indicators.

Table 4 Pearson's correlation coefficients between pairs of EP indicators, pooled data 2001-02 to 2008-09

	Cannot afford to keep home adequately warm	10% Indicator	LIHC Indicator
Cannot afford to keep home adequately warm	1.000		
10% Indicator	0.059***	1.000	
LIHC Indicator	0.057***	0.511***	1.000

Notes: The table reports Pearson's correlation co-efficients for each pair of Energy Poverty indicators. *** indicates the correlation is significantly different from zero at the 1% level. The data covers 55,772 observations from 10,465 households.

Figure 6: Percentage of 10%/LIHC EP households reporting IAAW, 2001-02 to 2008-09

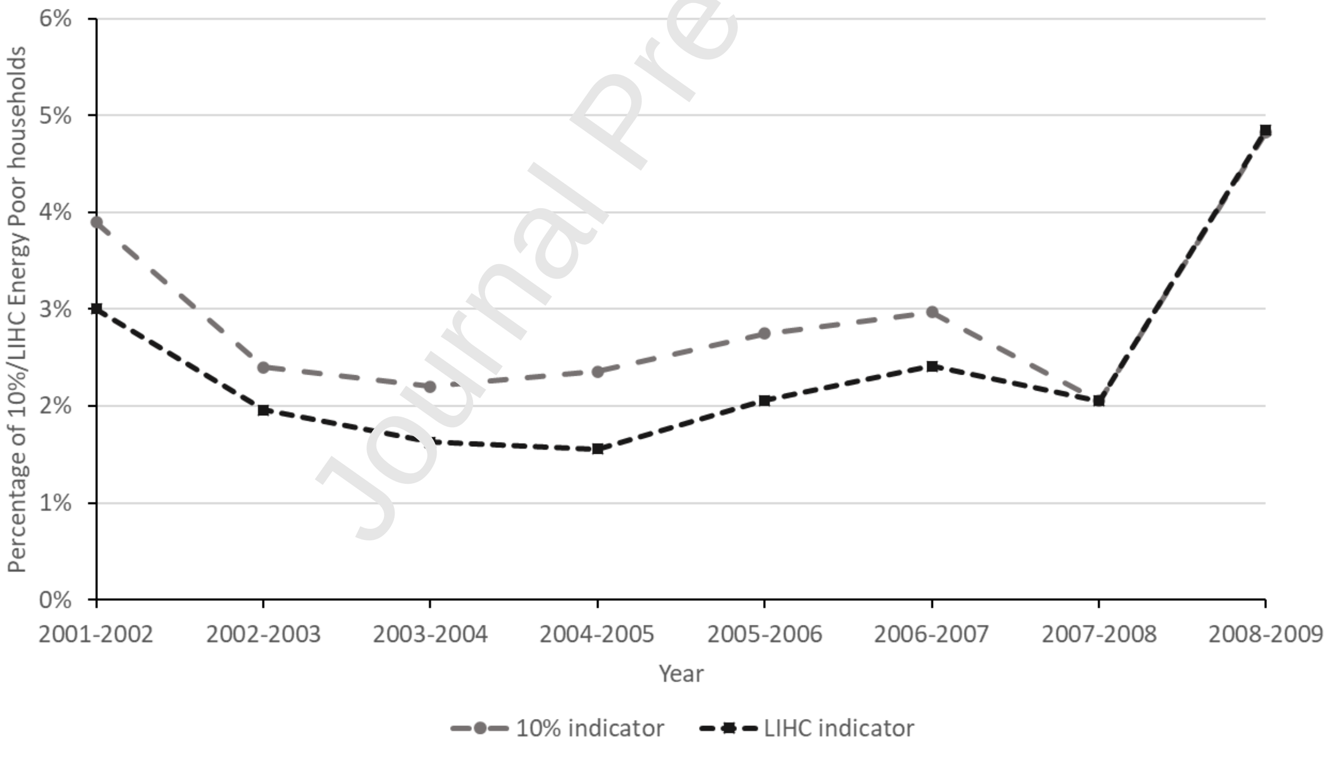


Figure 7: Percentage of households reporting IAAW identified as 10% or LIHC EP, 2001-02 to 2008-09

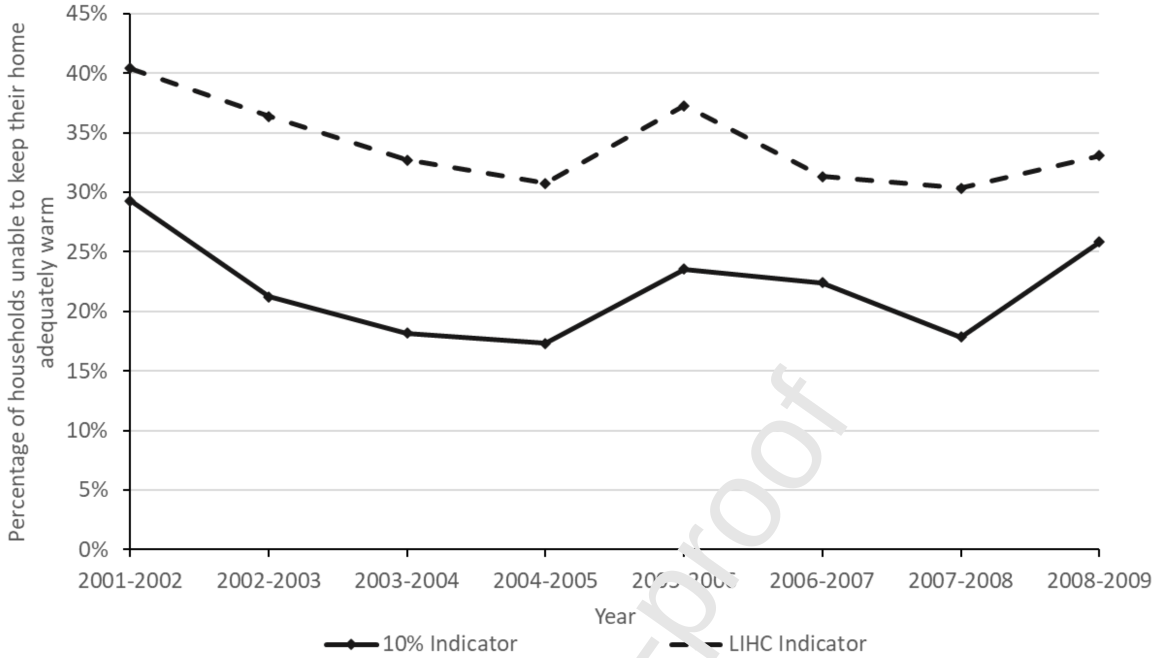


Figure 8: Percentage of households reporting IAAW by energy expenditure decile

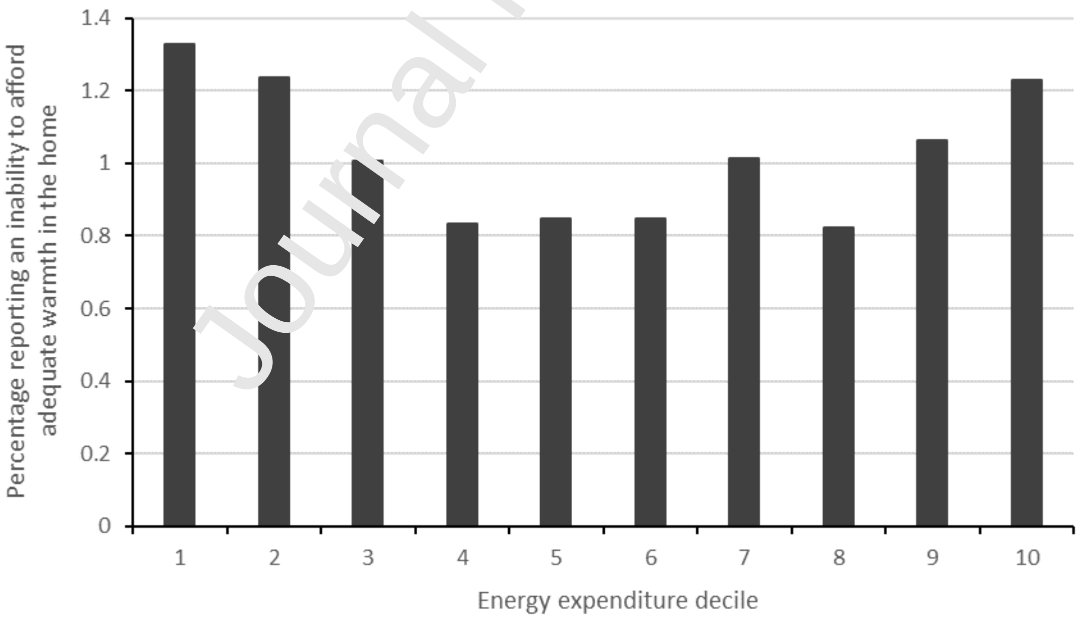


Figure 9: % reporting IAAW in each energy expenditure share decile, pooled data 2001-02 to 2008-09

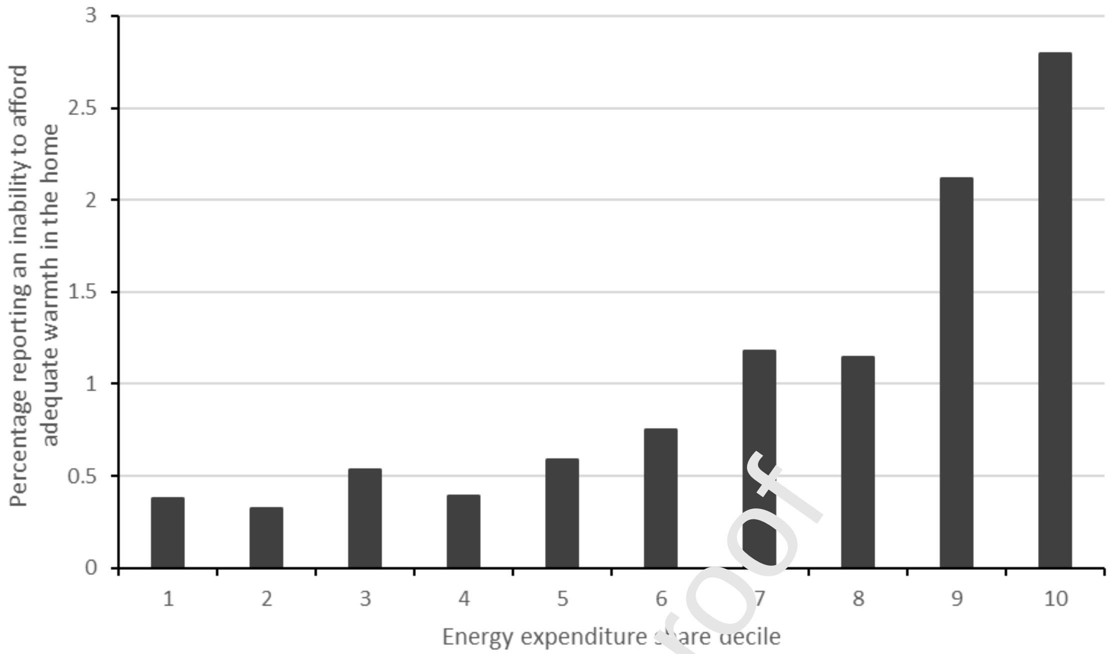


Figure 10: % reporting IAAW in each gross income decile, pooled data 2001-02 to 2008-09

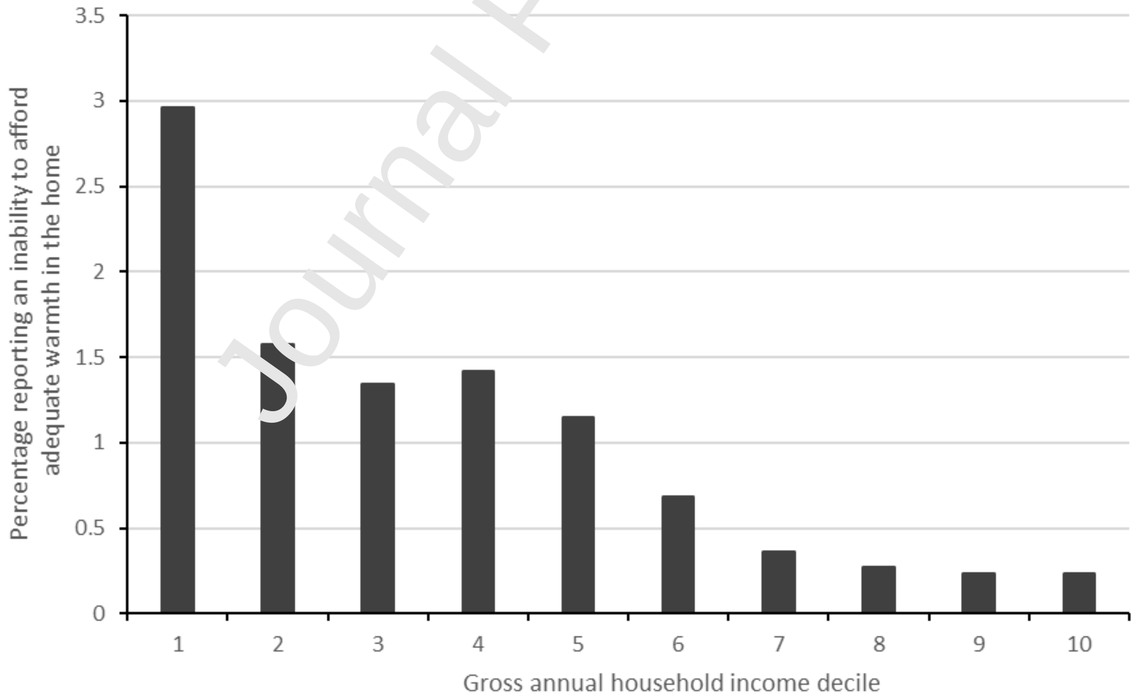
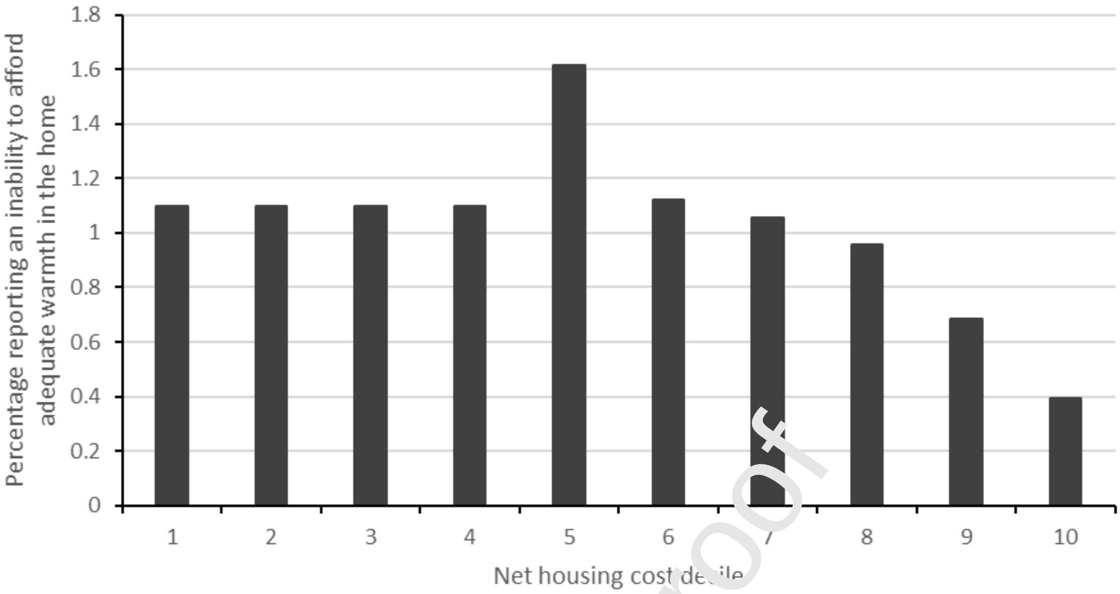


Figure 11: % reporting IAAW in each net housing cost decile, pooled data 2001-02 to 2008-09[23]



[23] In the first three deciles the net housing costs of all households is zero, while in the fourth decile all but 12 observations involve net housing costs of zero.

9. References

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Energy Poverty Indicators: Inconsistencies, Implications and Where Next?

HIGHLIGHTS

- Compares perception-based and expenditure-based Energy Poverty indicators in the UK
- Identifies inherent difficulties in interpreting results from different metrics
- Little overlap between expenditure and perception-based indicators is observed
- Each indicator identifies different household types as energy poor
- In-home temperature and temperature preference data are key for future research