
On the power of indicators: how the choice of fuel poverty indicator affects the identification of the target population

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Abstract :

In light of the creation of the EU Energy Poverty Observatory (EPOV) in January 2018 and the increase in debates on how fuel poverty is measured, we propose a critical analysis of fuel poverty indicators and demonstrate that choosing a given indicator is central to the identification of the fuel-poor population.

First, we conducted an inter-indicator analysis to show how profiles of fuel-poor households vary depending on the indicator selected. We designed a multidimensional approach based on a multiple correspondence analysis and a hierarchical and partitioning clustering analysis to study characteristics of fuel-poor households. We highlight the difficulty of identifying a fuel-poor '*typical profile*' and show that the composition of the population depends on the choice of the indicator.

Second, we applied an intra-indicator analysis using two objective expenditure-based indicators with thresholds. In particular, we conducted a sensitivity analysis based on a logit model including variables describing household and dwelling characteristics. We show that the profiles of fuel-poor households as well as the drivers of fuel poverty vary considerably with the chosen threshold level. Given these findings, we stress the need to review how we currently rely on conventional fuel poverty indicators to identify target groups and give some recommendations.

Keywords : Fuel poverty, group identification, indicator dismantling, multidimensional analysis, sensitivity analysis

JEL CLASSIFICATION : C20, C38, Q40, Q48

1 Introduction

Fuel poverty refers to a multidimensional concept that considers three main factors, namely the household financial situation, dwelling characteristics, *i.e.* energy efficiency, and energy prices (EPEE (2006), Devalière (2007), Palmer et al. (2008), Blavier et al. (2011)). A household is fuel-poor when it lives in an energy inefficient dwelling and is unable to heat its home at an appropriate standard level of warmth³ due to insufficient financial resources.

Despite the spread of fuel poverty in Europe and its recognition by governments as a social, public health and environmental policy issue in an context of ever-increasing energy prices, and despite the recent creation of the EU Energy Poverty Observatory (EPOV) on 29 January 2018, the European Union (EU) has not yet adopted a common definition of fuel poverty, nor common indicators to measure it.

The UK government was the first to acknowledge the phenomenon and set up measures to fight it. In fact, the fuel poverty concept was born in the UK in the 1970s under the leadership of activist organizations who called the issue to the attention of authorities and the general population in light of the winter mortality induced by the steady rise in energy prices preventing some households from heating their dwellings at an appropriate standard level of warmth (Dutreix et al. (2014), ONPE (2014), ONPE (2015)). Two decades later, Boardman (1991) based on an earlier contribution by Isherwood and Hancock (1979) defined an indicator that has since been used in the 2001 UK Fuel Poverty Strategy to measure fuel poverty⁴.

In France, the official definition of fuel poverty was published in the National Environmental Commitment Act (no. 2010-788 of 12 July 2010, “Loi Grenelle 2”) amending the Housing Rights Act (no. 90-449 of 31 May 31 1990, “Loi Besson”) ⁵. According to this definition, a fuel-poor household represents a person who has difficulties accessing energy inside his/her dwelling to satisfy his/her basic needs due to insufficient financial resources or inadequate dwelling characteristics *i.e.* energy inefficiency, presence of dampness and rot. Although it provided an official general framework for defining the fuel-poor, the French definition of fuel poverty remains impractical. In particular, it does not establish any clear-cut operational criteria to ensure the reliable identification of fuel-poor households and, therefore, appropriate implementation of policies to fight fuel poverty (Host et al., 2014). Recently, inspired by developments in the UK, the French National Observatory on Fuel Poverty (“*Observatoire National de la Pauvrete Energetique*”(ONPE)) uses various objective and subjective indicators to measure the magnitude of fuel poverty ((ONPE, 2014), (ONPE, 2015)).

Along the same lines, with the goal of combatting the problem, the French government passed the Energy Transition for Green Growth Act on 17 August 2015, which contains a social component calling for the prevention of fuel poverty by implementing short- and long-term policies. In particular, it set up curative measures to help fuel-poor households to pay their energy bills,

3. According to the World Health Organization (WHO), an appropriate standard level of warmth is equal to 21°C for the main living area and 18°C for other occupied rooms (ONPE, 2015).

4. According to Fahmy et al. (2011), “*the Warm Homes and Energy Conservation Act, effective from November 2000 and introduced with cross-party support, represents the first formal acknowledgement of fuel poverty as a social policy issue requiring governmental intervention. This act mandated the UK Government and Devolved Administrations to develop and implement a strategy for fuel poverty reduction, resulting in the 2001 UK Fuel Poverty Strategy. This official document committed the UK Government and Devolved Administrations for the first time to the ambitious goal of eliminating fuel poverty (DETR, 2001). Fuel poverty reduction targets include eliminating fuel poverty in England amongst “vulnerable” households by 2010, i.e. older persons, sick and disabled households and families with children, and amongst all households by 2016. These targets were reaffirmed in the 2007 Energy White Paper DTI (2007), and broadly similar targets are in place within the Devolved Administrations (DSDNI (2004), Scottish Executive (2002), WAG (2003))*”.

5. La “Loi Besson” no. 90-449 of 31 May 1990 stipulates that anyone encountering difficulties, particularly due to insufficient financial resources or inadequate living conditions, can benefit from the support of the community, according to the rules stipulated in the Act, to have access to decent and independent housing ensuring water, energy and telephone access - Translated from French (JORF, 1990).

36 *i.e.* income support, affordable fuel pricing and assistance with solvency in the case of arrears,
37 and preventive policies that focus on the improvement of dwelling energy efficiency, *i.e.* dwelling
38 insulation, double glazing, etc.

39 Prior to discussions on the effectiveness of these different policies, debates focused on the key
40 issue of reliably identifying fuel-poor households and describing their profiles. Within these debates
41 is the question of the relevance of fuel-poverty indicators used to identify the affected population.
42 The extent of the problem, the composition of groups and, therefore, the implementation of suit-
43 able public policies depend strongly on the types of indicator used to identify the fuel-poor and on
44 their construction.

45 In addition to discussing drawbacks of conventional indicators, one recurrent question deals with
46 the choice of the type of indicator to use to identify fuel-poor households: energy expenditure-based
47 indicators with thresholds, subjective self-reported indicators or consensual social indicators? In a
48 recent study, Heindl and Schuessler (2015) showed that most energy expenditure-based indicators
49 show odd dynamic behaviour in micro-simulations, and can thus lead to misleading or contra-
50 dictory conclusions on population identification. Considering the same type of expenditure-based
51 indicators, Hills (2012) previously argued that their construction can make them overly sensitive to
52 energy prices, and thus to a misidentification of the fuel-poor population. Similarly, because most
53 expenditure-based indicators are based on the definition of energy expenditures and/or income
54 thresholds, several criticisms based on discursive analyses have focused on the main impacts of the
55 choice of the type of threshold on the identification process⁶. Although some authors argue for the
56 use of an absolute threshold as in the case of the 10% indicator, others support the use of relative
57 thresholds based on means or medians of expenditures (Moore (2012), Boardman (2012), Liddell
58 et al. (2012)). Regardless of the type of threshold, the choice of the level to apply often lacks
59 theoretical foundation (Boardman, 2012). For example, the 10% threshold was set by doubling
60 the median energy expenditures based on the 1988 Family Expenditure Survey for UK households,
61 which has not been updated since. Beyond the question of the threshold, some other criticisms
62 focus on the choice of statistics used to build the indicators, for example the type of income, *i.e.*
63 full income, residual income, equivalised income and the type of energy expenditures, *i.e.* actual
64 and theoretical, estimated expenditures (Moore (2012), Heindl (2013)). Finally, other studies have
65 highlighted the need to fundamentally review how indicators are defined to account for the mul-
66 tidimensional nature of fuel poverty, which complicates the identification process. Fuel poverty
67 cannot be reduced to a solely monetary dimension, neglecting other important related issues such
68 as general deprivation (poverty), health, social exclusion and even environmental concerns.

69 A critical review of the literature on fuel poverty indicators raises two important issues. First,
70 because fuel poverty indicators have neither real theoretical foundations nor reached an empirical
71 consensus as to the identification of fuel-poor households, the use of one indicator rather than
72 another may prevent some affected households from being targeted by public policy measures de-
73 voted to eliminating the problem. Therefore, it is important to identify the trade-offs of each
74 indicator and how the indicators are applied. Second, the profiles of the fuel-poor may or may
75 not be homogeneous; it is important to determine how homogeneity can affect implementation,
76 reliability and the relevance of public policies targeting fuel poverty. To address these two issues,
77 we analyse in detail the impact of the choice of the fuel poverty indicator on the identification of
78 fuel-poor households, in particular, on the description of their profile. Our aim is to lend empirical
79 support to the discursive criticisms of current fuel-poverty indicators that highlight the influential
80 trade-offs operating during the design and monitoring stages of economic policies devoted to fight-

6. As far as we know, no quantitative analyses or empirical applications have been carried out in support of these criticisms.

81 ing fuel poverty. Moreover, within the framework of the recent creation of the EPOV, our aim
82 is to shed light on the importance of formulating an official European definition of fuel poverty
83 based on which either common or national indicators could be defined. This may, among others,
84 “improve transparency by bringing together the disparate sources of data and knowledge that exist
85 in varying degrees across the whole of the EU” and “promote informed decision making by local,
86 national and EU-level decision makers”⁷.

87 By using an original French database, named “Phébus” (*cf.* section 3 for more details), devel-
88 oped to study the fuel poverty issue in France, we demonstrate the variability in the profiles of
89 fuel-poor households across indicators and how their threshold level is constructed. The composi-
90 tion of fuel-poor households, and thus their characteristics, depend on which indicators is used.

91 The paper is structured as follows. In Section 2, we critically review existing fuel poverty
92 indicators. We distinguish three groups of indicators: objective factual indicators, subjective self-
93 reported indicators and composite indices. We detail their respective advantages and drawbacks.
94 In Section 3, we analyse how profiles of fuel-poor households vary across indicators and with the
95 indicator threshold. In particular, in Sub-section 3.1 we identify affected households using a set
96 of conventional objective and subjective indicators and we propose a multidimensional qualitative
97 approach based on multiple correspondence analysis (MCA) and a hierarchical and partitioning
98 clustering (HPC) method to analyse their characteristics⁸. Within this framework, we highlight
99 the difficulty of identifying a “*typical profile*” of a fuel-poor household due to the variability in
100 their profiles and show that the composition of the fuel-poor population depends on the choice
101 of the indicator. In Sub-section 3.2, based on two objective fuel poverty indicators, we conduct
102 an innovative sensitivity analysis using a logit model including variables describing household and
103 dwelling characteristics to demonstrate the limits of using exogenous indicator thresholds to de-
104 termine groups of fuel-poor households. Likewise, by considering the case of the French Energy
105 Voucher policy adopted as of January 2018 as a tool to fight fuel poverty and by using a sensitivity
106 analysis, we study how the target fuel-poor households vary depending on the policy threshold
107 currently aimed at the poorest 15% of households. We find that profiles of fuel-poor households,
108 as well as drivers of fuel poverty, vary considerably depending on the chosen threshold level. In
109 Section 4, we discuss our results and give some recommendations. Finally, in Section 5, we draw
110 some conclusions.

111 2 Critical review of fuel poverty indicators

112 In this section, we briefly present and discuss the advantages and drawbacks of fuel poverty
113 indicators that divide the general population into homogeneous groups. Figure 1 and Appendix A
114 summarise the content of this section.

115 2.1 Objective factual indicators

116 Objective factual indicators of fuel poverty are based on measurable and observable criteria.
117 We distinguish between expenditure-based indicators, the restriction-behaviour approach and con-
118 sensual social indicators.

119

7. Source: <https://www.energypoverty.eu/about/role-and-mission>.

8. Although our goals differ, Hache et al. (2017) is, as far as we know, the only study that has used a clustering analysis based on CHAID methodology to separate French household energy consumption into several homogeneous groups with regard to fuel poverty by relying on pre-identified predictors from the literature. Although that study offered a useful description of profiles of fuel-poor households, it still suffers from the criticisms that we address in this study with regard to identification of the fuel-poor.

121
 122 Expenditure-based indicators draw on notions from consumption economics. In particular,
 123 they take into account the amount of expenditures devoted to satisfy fuel needs with respect to
 124 the total available financial endowments. We examine here the 10% indicator (Boardman (1991)),
 125 the after-fuel-costs poverty (AFCP) indicator (Hills (2011)) and the low-income/high-costs (LIHC)
 126 indicator (Hills (2011, 2012)).

127
 128 — The 10% indicator

129
 130 The 10% indicator, also called the fuel poverty (FP) ratio, is calculated as follows:

$$\begin{aligned}
 \text{The 10\% indicator} &= \frac{\text{Theoretical fuel costs}}{\text{Equalised disposable income}} & (1) \\
 &= \frac{(\text{Theoretical fuel consumption} \times \text{fuel price})}{\text{Equalised disposable income}}
 \end{aligned}$$

131 A household is considered fuel-poor if it spends more than 10% of its equivalised dispos-
 132 able income (before housing costs) on fuel supply to maintain an appropriate standard level
 133 of warmth inside its dwelling⁹. The equivalised disposable income is the total income of a
 134 household, after taxes and other deductions, that is available for spending or saving, divided
 135 by the number of household members converted into equivalised adults, *i.e.* number of con-
 136 sumption units (*cu*). Household members are equivalised or made equivalent by weighting
 137 each according to their age using an official equivalence scale.

138 The 10% indicator considers theoretical rather than actual/observed fuel costs. These costs
 139 are modelled by multiplying fuel requirements by fuel prices. These requirements are calcu-
 140 lated based on a number of factors including primarily the size of the dwelling, the number
 141 of people who live in it, its energy efficiency level and the fuels used. In addition, theoreti-
 142 cal fuel costs capture four areas of fuel consumption, namely space heating, water heating,
 143 lights and appliances and cooking needs (DECC, 2014). Typically, the majority of the
 144 fuel bill goes towards space heating¹⁰. It is generally difficult to calculate theoretical fuel
 145 costs. Therefore, an alternative widespread way to determine the 10% indicator is to use
 146 actual/observed fuel costs.

147 Although this indicator has the advantage of taking into account under-consumption by
 148 comparing theoretical and actual fuel consumption, it is not intended to measure whether
 149 households are spending more than 10% of their income on domestic fuel, but rather whether
 150 they would need to do so to reach an acceptable warmth level in their dwelling on the basis
 151 of observed income and modelled physical data related to dwelling space and thermal effi-
 152 ciency (Fahmy et al. (2011), Legendre and Ricci (2015)). Moreover, when based on actual
 153 fuel costs, the 10% indicator does not take into account the restriction or deprivation prac-
 154 tices of some households, *i.e.* under-heating with regard to heating needs, induced by high
 155 fuel costs (Dutreix et al., 2014).

156 Using the same criticism, Hills (2011) and Moore (2012) argue that the 10% indicator does
 157 not reliably take into account the income level, particularly in the case of households with
 158 high income. In effect, in essence, when used to determine the extent of fuel poverty, the
 159 10% indicator does not include a cut-off for households with high income. Therefore, a

9. *Cf.* footnote number 3 for an official definition of an appropriate level of warmth.

10. In the UK in 2013, on average, around 51% of the theoretical household bill was devoted to space heating, 34% for lighting and appliances usage, 12% for water heating and 3% for cooking (DECC, 2014).

160 significant number of them are found to be fuel-poor, although in reality their high fuel
 161 expenses are proportional to their high income. More fundamentally, although the 10%
 162 indicator is applied to different national contexts, it is definitely not suitable for compar-
 163 isons because it was defined in reference to a now-obsolete and country-specific threshold
 164 of energy expenditures. It represents the double of median energy expenditures determined
 165 based on the 1988 Family Expenditure Survey for UK households. Since that date, it has
 166 not been updated.

167

168 — The after-fuel-costs poverty (AFCP) indicator

169

170 The AFCP indicator was developed by Hills (2011). It is based on the comparison be-
 171 tween the household equivalised income and the standard threshold of 60% of equivalised
 172 national income, where income is considered after subtracting housing and domestic fuel
 173 costs.

174 According to this indicator, there is a situation of fuel poverty if:

$$\begin{aligned} \text{Equalised (Income - Housing costs - Domestic fuel costs)} &< \\ 60\% \text{ Equalised (Median income - Housing costs - Domestic fuel costs)} &\quad (2) \end{aligned}$$

175 Although it is not based on the constrained income, which represents the income after sub-
 176 tracting all constrained expenditures that should be met before turning to fuel expenditures
 177 such as taxes, transport, health and education, one advantage of the AFCP indicator is that
 178 it takes into account housing costs. They represent only part of the constrained expendi-
 179 tures, but when included in calculations, they enhance the reliability of results. Another
 180 advantage of the AFCP indicator is that it can identify the aggravating effect of fuel poverty
 181 on monetary (income) poverty. It is indeed plausible that people with already high fuel costs
 182 are pushed into monetary poverty because of these high fuel costs. However, one drawback
 183 of the AFCP is that a high proportion of households with very low incomes will be classified
 184 as fuel-poor regardless of their fuel requirements. Therefore, confusion between fuel and
 185 monetary poverty can occur (Legendre and Ricci, 2015).

186

— The low-income/high-costs (LIHC) indicator

Defined by Hills (2011, 2012), the LIHC indicator considers two thresholds to identify fuel-
 poor households. The first is the household equivalised disposal income that should be less
 than 60% of the equivalised national median disposal income. The latter is equal to the
 equivalised income net of housing and domestic fuel costs¹¹. The second threshold defines
 a standard level of fuel expenditures. In particular, the household equivalised fuel expen-
 ditures should be equal to or greater than the required national median fuel expenditures.
 Therefore, according to this approach, a household is fuel-poor if:

$$\left\{ \begin{array}{l} \text{Equalised net income} \leq 60\% \text{ (Equalised median net income)} \\ \text{and} \\ \text{Equalised fuel expenditures} \geq \text{Required national median fuel expenditures} \end{array} \right. \quad (3)$$

187 We distinguish between the LIHC (m^2) and (cu). The LIHC (m^2) indicator equalises fuel

11. Therefore, this income threshold corresponds to the definition of the AFCP indicator.

188 expenditures by dividing them by the surface area of the dwelling in square meters (m^2),
189 whereas the LIHC (cu) indicator equalises fuel expenditures by dividing them by the num-
190 ber of consumption units (cu) of the household. The LIHC is a dual indicator that measures
191 not only the extent of fuel poverty (how many fuel-poor households there are) but also the
192 depth of the problem (how badly affected each fuel-poor household is). The depth of fuel
193 poverty is calculated by taking into account the fuel poverty gap, which is a measure of
194 the additional fuel costs faced by fuel-poor households, to meet the non-fuel-poor household
195 threshold.

196 With respect to the AFCP indicator, the advantage of the LIHC indicator is that it clearly
197 distinguishes between fuel and monetary poverty by applying two different thresholds. How-
198 ever, as in the case of the AFCP indicator, the LIHC indicator is based on the calculation
199 of the net income after housing and domestic fuel costs. Moreover, it does not take into
200 account the heat-restriction behaviour of some households.

201 *The restriction-behavior indicator and consensual social indicators*

202
203
204 Indicators based on restriction behaviour stand out from other expenditure-based indicators,
205 but still belong to the class of objective indicators. Restriction-behaviour indicators are based on
206 the calculation of the actual and the theoretical fuel consumption necessary to reach an appropri-
207 ate dwelling level of warmth¹² and on the determination of the difference between them. When
208 calculated, the theoretical fuel consumption takes into account the dwelling's energy efficiency.

209 In addition to quantifying restriction behaviour, this approach can also determine which house-
210 holds have a suitable cost analysis for performing dwelling retrofit energy investments (Charlier
211 (2013, 2014)). The main difficulty encountered when calculating this indicator is the assessment
212 of theoretical fuel consumption¹³.

213 Also belonging to the group of objective factual indicators and in addition to the expenditure-
214 based and restriction-behaviour indicators, consensual social indicators are also used to assess
215 the magnitude of fuel poverty. They are based on the monetary poverty and deprivation litera-
216 ture, which go beyond the observations exposed in the recently developed fuel poverty literature
217 (Townsend (1979), Callan et al. (1993), Gordon et al. (2000)). These indicators stipulate that
218 some goods and services are considered as necessary for a person to be able to conduct a socially
219 dignified lifestyle. They are regarded as essential attributes and are perceived as socially necessary.
220 Therefore, according to the consensual social approach, when considering the energy context, a
221 deprivation state with regard to basic household utility needs is considered as an indicator of fuel
222 poverty. In other words, the use of consensual social indicators aims to capture the wider elements
223 of fuel poverty, namely energy poverty by focusing on social exclusion and material deprivation,
224 as opposed to approaches based solely on expenditure-based indicators. The use of consensual
225 social indicators relies on the combination of several dimension of energy poverty such as cooking,
226 lighting, communication, education, etc.

227 **2.2 Subjective self-reported indicators**

228 Subjective fuel poverty indicators are based on personal opinions, interpretations, points of
229 view and judgment. They are usually constructed by referring to households' self-reported answers

12. *cf.* footnote number³ for a standard definition of an appropriate level of warmth.

13. Charlier (2013, 2014) assessed theoretical fuel consumption using Promodul software by taking into account dwelling characteristics and by referring to the 3CL-DPE method presented in the French Energy Performance Diagnosis Act of September 2006 for existing buildings put up for sale in France (JORF, 2006).

230 on questions asked by social investigators during a survey. The most frequently asked questions
231 include:

- 232 — Do you suffer from thermal discomfort?
- 233 — Have you had difficulty in paying your utility bills (in the past)?
- 234 — Can you afford your energy bills?
- 235 — Are you satisfied with your heating equipment?

236
237 Several studies use subjective indicators to study fuel poverty. For example, Healy (2003) con-
238 siders three subjective indicators based on the questions listed above to analyse the fuel poverty
239 in Ireland and the EU. Also, the INSEE ENL (2006) and EPEE (2006) analyses of fuel poverty
240 are based on subjective indicators. In particular, EPEE (2006) defines fuel poverty as “*the house-*
241 *hold’s difficulty, sometimes even the inability, to adequately heat its dwelling at a fair price*”, and
242 in the French dwelling survey (INSEE ENL (2006)), households are asked to answer the question
243 “*Did you suffer from the cold for at least 24 hours in your home last winter?*”. Within the same
244 framework, Price et al. (2012), in exploring the links between objective and subjective indicators
245 of fuel poverty in UK, use a subjective self-declared indicators of fuel poverty based on whether
246 consumers feel able to afford their energy bills.

247 Since these subjective indicators are constructed on the basis of self-reported answers strongly
248 correlated with different personal standards, results of different studies should be interpreted with
249 caution mainly with respect to the identification of fuel-poor households. In particular, the in-
250 terpretation of results may contradict those based on objective factual indicators, although the
251 introduction of self-reported indicators provides valuable information in terms of identifying the
252 fuel-poor and of policy development (Price et al., 2012).

253 2.3 Composite indices

254 Composite indices were created as a compromise between the simplicity of one-dimensional
255 indicators and the need to account for the multidimensional nature of fuel poverty. They rep-
256 resent an attempt to overcome the shortcomings of one-dimensional indicators and, at the same
257 time, produce a result that condenses the information into single and easy-to-interpret metrics
258 (Thomson and Snell, 2013). Based on a set of sub-indicators, these indices aim to associate several
259 attributes of fuel poverty that cannot be reliably depicted in a single indicator. Several attempts
260 have been made to construct composite indices for developed countries for which the main focus is
261 selecting which aspects of poverty to take into account, *i.e.* energy prices, income, dwelling energy
262 efficiency, personal judgment (Thomson and Snell (2013), Fabbri (2015), Charlier and Legendre
263 (2016), Okushima (2017)). Although these attempts make a significant contribution, there is still
264 a room for improvement in the measurement of fuel poverty. For example, based on the more
265 exhaustive conceptual framework of the energy poverty literature applied to developing countries,
266 which focuses on the issue of access to energy rather than thermal discomfort as in developed coun-
267 tries, Nussbaumer et al. (2012) propose new multidimensional indicators to measure fuel poverty.

268 The main drawback of composite indices is that combining variables causes some form of infor-
269 mation reduction or loss, with all the associated methodological issues and required assumptions
270 and simplifications it implies (including value judgments). Therefore, if not meticulously handled,
271 composite indices can be seriously misleading when identifying the fuel-poor and defining public
272 policies.

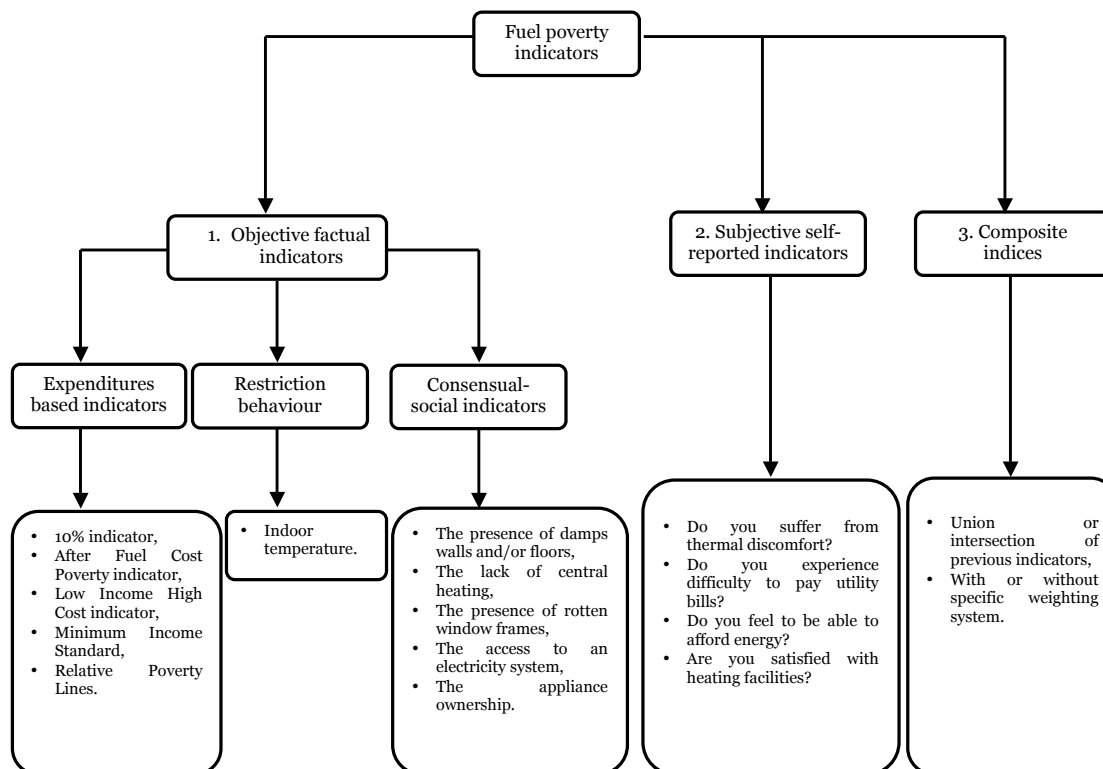


Figure 1. Summary of fuel poverty indicators. Source: authors elaboration.

3 Which households are fuel-poor?

In this section, we show how difficult it is to identify fuel-poor households.

To do so, we start by calculating fuel poverty rates, or equivalently, determining the population of fuel-poor households. We use data extracted from the “Phébus” database (*“Performance de l’Habitat, Equipements, Besoins et Usages de l’énergie”*) which is especially devoted to the in-depth analysis of the fuel poverty issue in France. This database was compiled from April to October 2013 by the Ministry of Ecology, Sustainable Development and Energy (*“Ministère de l’Ecologie, du Développement durable et de l’Energie”* (MEDDE)), the General Commission for Sustainable Development (*“Commissariat Général au Développement Durable”* (CGDD)), and the Department of Observation and Statistics (*“Service de l’observation et des statistiques”* (SOeS)). It is divided into two parts: (1) a face-to-face interview with the occupants of the home about their energy consumption, expenditures and attitudes and (2) an energy efficiency diagnosis of the dwelling. In particular, “Phébus” contains information describing the household, *i.e.* the amount of energy expenditures, attitudes toward energy consumption, disposable income, age, etc., and dwelling characteristics, *i.e.* surface, type of heating system, level of energy efficiency, etc. Therefore, it can study the household’s energy consumption in detail and the associated issue of fuel poverty. The “Phébus” database covers the year 2013.

We calculated fuel poverty rates for 2013 using two objective expenditure indicators, *i.e.* the 10% and the LIHC (m^2) indicators, and one subjective indicator, *i.e.* the Thermal Discomfort indicator. This indicator relies on the answer of households to the following question “*Did you suffer from the cold in your dwelling for at least 24 hours last winter?*”¹⁴.

14. We calculated the fuel poverty rate using the LIHC (cu) indicator. Because results are quite similar to those of the LIHC (m^2), we do not report them here to save space. They are however available upon request.

294 In Appendix B, we detail how we compute fuel poverty rates using the 10%, LIHC (m^2) and
295 Thermal Discomfort indicators. Our initial data set was composed of 5405 households. Our results
296 show that 14.16% (766), 10.95% (592), 9.52% (514), and 7.75% (419) of households are fuel-poor
297 according to the 10%, LIHC (m^2), LIHC (cu), and Thermal Discomfort indicators, respectively.

298 Then, after identifying fuel-poor households, we focused in Sub-sections 3.1 and 3.2 below on
299 the variability of the profiles. Therefore, we conducted inter-indicator and intra-indicator vari-
300 ability analyses. The inter-indicator variability indicates how profiles of fuel-poor households vary
301 depending on the indicator used to identify fuel-poor population (Sub-section 3.1). The intra-
302 indicator variability deals with the construction of the indicator and means that when varying the
303 threshold level of a given indicator¹⁵ profiles of fuel-poor households vary (Sub-section 3.2)

304 **3.1 Inter-indicator analysis: how profiles of fuel-poor households vary** 305 **across indicators**

306 To analyze how profiles of fuel-poor households vary across indicators, we used three comple-
307 mentary methods. The first is a multiple correspondence analysis (MCA), which is a variation on
308 the principal component method. The second is the hierarchical clustering (HC) method. The
309 third is the partitional clustering method (PC).

310 Principal component methods include three types of analyses:

- 311 — Principal component analysis (PCA), which is suitable for analyzing databases containing
312 quantitative/continuous variables;
- 313 — Correspondence analysis (CA), which is used to handle a data set composed of two quali-
314 tative/categorical variables;
- 315 — Multiple correspondence analysis (MCA), which is an extension of simple CA used to anal-
316 yse a database containing more than two categorical variables.

317
318 The core idea common to all principal component methods is to describe a dataset (X with I in-
319 dividuals and K variables) using a small number ($S < K$) of uncorrelated variables that retain
320 as much information as possible. The reduction in variables is achieved by transforming the data
321 into a new set of continuous variables called principal components (Husson et al., 2016). One
322 major advantage of principal component methods, in particular MCA, is that it can analyse the
323 multidimensional character of a dataset as in the case of the fuel poverty issue. Therefore, we ran
324 an MCA on each sample of fuel-poor households determined in the previous sub-section based on
325 the (objective) 10% and LIHC indicators and on (the subjective) Thermal Discomfort indicator¹⁶.

326 By extension, because PCA is considered as a pre-process for clustering¹⁷, we used our MCA
327 results to perform hierarchical and partitional clustering (HPC). We sought to classify fuel-poor
328 households with similar characteristics into homogeneous groups and compare the results (mainly)
329 across indicators, although we can also analyse the variability of profiles for a given indicator. Hier-
330 archical clustering was based on Ward’s criterion. This criterion refers to Huygen’s theorem, which
331 decomposes the total inertia (total variance) into between- and within-group variance. More pre-
332 cisely, Ward’s criterion consists in aggregating two clusters to minimise the growth of within-group

15. We focus here on the class of “expenditure-based indicators” where most indicators are based on the definition of a threshold (*cf.* Section 2).

16. For the LIHC indicator, to save space, we present results only for LIHC (m^2). Results for LIHC (cu), which corroborate our global results, are available upon request.

17. PCA can effectively be viewed as a “noise removal” method. The first dimension extracts the essential information and the subsequent dimensions are restricted to noise. Without noise in the data, clustering is more stable.

333 inertia (in other words, minimising the reduction of the between-group inertia). The within-group
334 inertia characterises the homogeneity of a cluster. The hierarchy is represented by a hierarchical
335 tree, *i.e.* a dendrogram, which is indexed by the increase in within-group inertia (Husson et al.,
336 2016). This hierarchical tree can be considered as a sequence of nested partitions, ranging from
337 one in which each individual is a cluster to one in which all the individuals belong to the same
338 cluster. The number of clusters can then be chosen looking at the overall appearance (or the
339 shape) of the tree, alongside the bar plot of the increase in within-group inertia, etc. These rules
340 are often based – implicitly or not – on the growth of inertia. Different strategies are available to
341 define clusters (partitioning). The simplest one consists in keeping the Q clusters defined by the
342 hierarchical tree. A second strategy consists in performing a K-means algorithm with the number
343 of clusters set to Q . Another strategy combines the two previous ones. In our study, we used the
344 K-means algorithm under which two conditions must be satisfied: (1) each group contains at least
345 one point, and (2) each point belongs to exactly one group.

346 To select the variables to incorporate in the MCA/HPC, or equivalently, which variables best
347 describe the fuel poverty situation, thus a “*typical profile*” a fuel-poor household, we reviewed the
348 literature on fuel-poverty drivers. In Appendix C, we summarise our literature review, based on
349 which we selected the 19 most relevant variables from the “Phébus” dataset to depict fuel poverty.
350 In Table 1, we give these variables that describe both household and dwelling characteristics. To
351 enhance the analysis, we also considered other variables related to the subjective perception of
352 indoor cold, heating restriction behaviour, climate zone and the type of geographic setting.

Table 1 – Variables included in the MCA/HPC (with “Phébus” codes given in parentheses)

	Variable name and code in the “Phébus”database
Household characteristics	Sex of the household reference person (SEXE) ¹⁸ Age of the household reference person (AGEPR) Socio-economic group of the household (PCS2003) Size of the household (UC) Disposable income (REVENU DISPONIBLE 2012) Difficulty of paying energy bill (ETDIFF) Beneficiary of national social tariff for energy (ETSOC) Ownership and use of motor vehicles during the last 12 months (EVEHIC)
Dwelling characteristics	Type of dwelling (EHTLC) Surface of dwelling (EHST) Tenure Type (ESTOC) Type of heating system (EKMOD) Presence of an air-conditioner (EKCLIM1) Year of dwelling construction (BATI PERIODE) Renovation and dwelling upgrading works (EQMOTIV) ¹⁹
Other variables	Did you restrict your use of heating last winter? (ERESTRIC1) Did you suffer from the cold for at least 24 hours in your home last winter? (EGCHAUF) Climate zone (Zone climatique 1 position) Type of geographic setting (RP TAILLE UU)

353 Then, based on the MCA output, we ran an HPC²⁰. For each indicator, HPC divides the sam-
354 ple of fuel-poor households into sub-groups, or clusters, having the same characteristics. With this

18. The code name in parentheses associated with each variable in this table refers to the code name of the variable in the “Phébus”database.

19. Depending on data, we consider 2 types of renovation and upgrading works. The first is devoted to decrease energy consumption and to improve heating system quality ($EQMOTIV_4$). The second aims to upgrade dwelling after an energy efficiency diagnostic ($EQMOTIV_5$).

20. To save space and avoid unnecessary detail, we do not give the results of the MCA. We focus on analysing results of the HPC based on which we split the initial set of observed households into several groups having the same profiles. Methodological aspects on how we ran the MCA as well as its results are available upon request.

355 detailed description of the fuel-poor by type of indicator, we compared profiles across indicators:
356 which variables best describe the fuel-poor and do their profiles vary across indicators? In other
357 words, do identification processes vary depending on which indicator is used?

358 Results for the three types of indicator are shown in Figure 2. They show that fuel-poor house-
359 holds are partitioned into four clusters for the 10% and LIHC (m^2) indicators and into three clusters
360 for the Thermal Discomfort indicator. Households belonging to the same cluster are homogenous,
361 but differ between clusters. Regardless of the cluster, Table 2 shows that, for each indicator, the
362 ranking of the most represented variables (or associated levels) is different. For example, whereas
363 the first three variables describing the best clusters of the fuel-poor determined using the 10% in-
364 dicator are “Beneficiary of the national social tariff for electricity”, “Age”, “Socio-economic group”,
365 for the LIHC (m^2) indicator, they are “Age”, “use of communal central heating system²¹”, and “use
366 of individual central heating system²¹”. For the Thermal Discomfort indicator, the three most
367 important variables supporting the identification process are “Age”, “Type of dwelling”, and “Socio-
368 economic group”. Although this indicator shares variables with the 10% indicator (“Socio-economic
369 group” and “Age”) or with the LIHC (m^2) indicator (“Age”), the variable “Type of dwelling” also
370 supports the identification of the fuel-poor according to it.

371 These preliminary results of the HPC analysis show that although profiles of the fuel-poor are
372 determined according to a set of common variables, or equivalently common characteristics, the
373 importance of each variable in profile identification varies across indicators. This means that the
374 composition of groups depends on which indicator is used. In this context, considering the eight
375 highest ranked variables²², Tables 3, 4, and 5 detail the composition of the fuel-poor population
376 for the 10%, LIHC (m^2), and Thermal Discomfort indicators, respectively²³.

377 *Cross-indicator comparison of profiles of the fuel-poor belonging to the most representative clusters*

378
379
380 To interpret our results, we consider, for each indicator, clusters of the fuel-poor with the
381 highest weight, *i.e.* cluster 2 including 40.38% of the total fuel-poor population for the 10% indi-
382 cator (*cf.* Table 3), cluster 1 including 31.43% of the total fuel-poor population for the LIHC (m^2)
383 indicator (*cf.* Table 4), and cluster 1 including 41.68% of the total fuel-poor population for the
384 Thermal Discomfort indicator (*cf.* Table 5). By simultaneously considering the three indicators,
385 we also identified the most represented common variables, namely “Age”, “Socio-economic group”,
386 “Type of dwelling”, “Surface of dwelling”, and “Type of heating system”. Given these two elements,
387 our results show that the fuel-poor identified using the 10% and LIHC (m^2) indicators have similar
388 characteristics with respect to the type and the surface of their dwellings, but different features
389 with respect to their age, socio-economic group and type of heating system. In particular, the
390 two populations of fuel-poor live in large and detached houses, *i.e.* $> 100 m^2$. Nevertheless, the
391 fuel-poor in cluster 2 using the 10% indicator are aged from 41 to 60, are workers and have an inde-
392 pendent space heater(s) (or independent heating in each room), whereas those belonging to cluster
393 1 and determined using the LIHC (m^2) indicator are elderly, *i.e.* > 61 years, belong to a high
394 socio-economic group, *i.e.* managers or equivalent status, and use an individual central heating
395 systems (boiler or other type of central heating). By extension, when looking at the composition of

21. The original variable was “The type of heating system”.

22. In the interest of concision, and because the conclusions are the same, we do not show the results for all 19 variables of the HPC analysis. They are available upon request.

23. To compare profiles across indicators, we shaded the common variables in grey and we indicated the rank of (all) variable(s) or associated levels in parentheses as already presented in Table 2. Some variables have a double ranking. For example, the variable “Type of heating system” from Table 3 is ranked 5 and 6. This means that the two levels associated with this variable appear as the 5th and 6th most represented levels. They respectively correspond to the “Yes” or “No” answers to the two following questions: “Do you lack a heating system in your dwelling?” and “Do you know what type of heating system do you have in your dwelling?”

396 the most important part of the fuel-poor population identified using the Thermal Discomfort indi-
397 cator, *i.e.* cluster 1, results show important differences with regard to the profiles of the fuel-poor
398 using the 10% and LIHC (m^2) indicators. The fuel-poor identified using the Thermal Discomfort
399 indicator are very young, *i.e.* < 20 years, working (not attending an educational institution),
400 living in apartments located in large cities such as Paris and use an independent space heater(s)
401 (independent heating in each room) or communal central heating system (communal boiler or heat
402 pump).

403 In sum, comparing the most representative clusters of fuel-poor population across indicators
404 demonstrates that the differences between profiles are greater than their similarities.

405

406 *Cross-indicator comparison of the profiles of the fuel-poor belonging to the less representative clus-*
407 *ters*

408

409 As shown in Tables 3, 4, and 5, the less representative clusters are cluster 4 for the 10%
410 indicator, cluster 4 for the LIHC (m^2) indicator, and cluster 3 for the Thermal Discomfort indica-
411 tor. They respectively include 1.38%, 12.40%, and 22.26% of the total fuel-poor population. When
412 comparing the profiles of the fuel-poor across indicators, in particular, profiles identified using the
413 LIHC (m^2) indicator and those based on the Thermal Discomfort indicator²⁴, our results show
414 significant differences in dwelling characteristics. Although the fuel-poor identified based on the
415 LIHC (m^2) indicator are young employees, *i.e.* < 20 years, living in small apartments, *i.e.* [1-40
416 m^2], and having a communal central heating system (communal boiler or heat pump), those iden-
417 tified based on the Thermal Discomfort indicator are generally older [41-60 years], employed as
418 non-qualified workers, living in a detached house and having another type of heating system (not
419 identified) (*cf.* Table footnote number³⁹).

420

421 *Comparison of the fuel-poor profiles across classes of indicators: objective vs. subjective indi-*
422 *cators*

423

424 In addition to the variability of profiles across indicators, our results show that these dif-
425 ferences are heightened when switching from one class of indicator to another, *i.e.* when switching
426 from objective indicators (10% and LIHC (m^2)) to a subjective (Thermal Discomfort) indicator.
427 In this context, when considering cluster 3 of the fuel-poor population identified using the 10% and
428 LIHC (m^2) objective indicators, our results show striking similarities between profiles with respect
429 to age, *i.e.* [21-40 years], the socio-economic group, *i.e.* police officer/military personnel, the type
430 and surface of dwelling, *i.e.* detached house, and the type of heating system, *i.e.* individual all-
431 electric heating (all-electric heating includes mounted radiators/convectors installed in every room
432 and not inter-connected to a boiler or furnace). However, when comparing these profiles with those
433 determined based on the subjective Thermal Discomfort indicator criteria, our results point out
434 differences mainly with regard to the socio-economic group, *i.e.* farmer or technician *vs.* police
435 officer/military personnel, the surface of the dwelling, *i.e.* [40-70 m^2] *vs.* [100-150 m^2], and the
436 type of heating system, *i.e.* individual all-electric heating *vs.* individual central heating (boiler or
437 other type of central heating).

438

24. Because the description of dwelling characteristics of the fuel-poor identified using the 10% indicator is not available, it is not judicious to compare these profiles with those identified using the LIHC (m^2) and Thermal Discomfort indicators. The missing information on the dwelling characteristics means that none of the variables are significantly represented in the cluster even if it can be significantly represented inside the total fuel-poor population, *i.e.* P-value $< 2\%$ (Husson et al., 2016).

439 In sum, the HPC made it possible to analyse in detail the characteristics of the fuel-poor
 440 population across indicators. It mainly highlighted that the composition of the fuel-poor popu-
 441 lation varies with the indicator. In particular, as presented in Table 2, some variables are more
 442 important than others when identifying affected groups, leading to significant profile variability
 443 across indicators. Therefore, it is still difficult to identify the fuel-poor population and to depict
 444 a “*typical profile*”. Even if we succeed, this typical profile may exclude a high number of fuel-poor
 445 households, depending on the indicator selected. Some households that are fuel-poor according to
 446 one indicator are not necessarily fuel-poor according to another. In this context, our results show
 447 that in our sample only 259 households are fuel-poor according the 10%, the LIHC (m^2), and the
 448 subjective Thermal Discomfort indicators simultaneously, whereas 766 households are fuel-poor
 449 according to the 10% indicator, 592 according to the LIHC (m^2), and 419 according the Thermal
 450 Discomfort indicator.

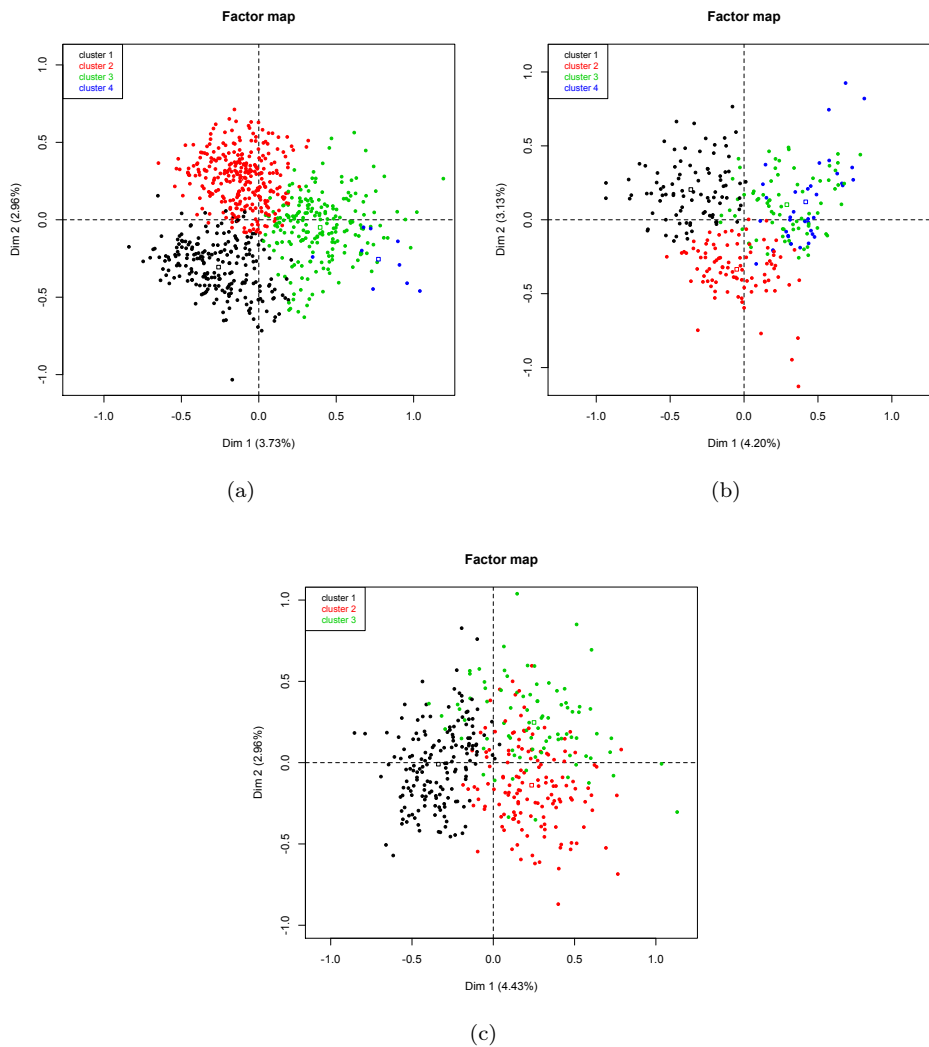


Figure 2. (a) Clusters according to the 10% indicator, (b) Clusters according to the LIHC (m^2) indicator, (c) Clusters according to the Thermal Discomfort indicator

Table 2 – Ranking of the most represented variables within clusters of fuel-poor households (based on a χ^2 test)

	Fuel poverty indicator		
	10%	LIHC (m^2)	Thermal Discomfort
Household characteristics			
Sex of the household reference person (SEXE)	[9]	[20]	[19]
Age of the household reference person (AGEPR)	[2]	[1]	[1]
Socio-economic group of the household (PCS2003)	[3]	[4]	[3]
Size of the household (UC)	—	—	—
Disposable income (REVENU DISPONIBLE 2012)	[10]	[13]	[10]
Difficulty in paying energy bill (ETDIFF)	[13]	[19]	[11]
Beneficiary of national social tariff for energy (ETSOC)	[1] ²⁵ , [4] ²⁶ , [23] ²⁷ , [12] ²⁸ , [19] ²⁹	[14] ²⁷ , [23] ²⁹ , [21] ²⁶ ,	[15] ²⁸ , [21] ²⁷ ,
Ownership and use of motor vehicles during the last 12 months (EVEHIC)			
Dwelling characteristics			
Type of dwelling (EHTLC)	[7]	[7]	[2]
Surface of dwelling (EHST)	[8]	[5]	[8]
Tenure Type (ESTOC)	[11]	[6]	—
Type of heating system (EKMOD)	[5] ³⁰ , [6] ³¹ , [22] ³² , [15] ³³ , [17] ³⁴ , [21] ³⁵	[2] ³⁵ , [3] ³³ , [10] ³² , [15] ³⁴ , [16] ³⁶ , [17] ³⁰ , [18] ³¹ , [22] ³⁷	[4] ³⁵ , [5] ³³ , [12] ³⁸ , [13] ³² , [14] ³¹ , [18] ³⁹ , [19] ³⁴
Presence of an air-conditioner (EKCLIM1)	—	—	[22]
Year of dwelling construction (BATI PERIODE)	[18]	[12]	[7]
Renovation and dwelling upgrading works (EQMOTIV)	—	—	—
Other variables			
Did you restrict your use of heating last winter? (ERESTRIC1)	[20]	[11]	[9]
Did you suffer from the cold for at least 24 hours last winter? (EGCHAUF)	[16]	[9]	[16]
Climate zone (Zone climatique 1 position)	—	—	[20]
Type of geographic setting (RP TAILLE UU)	[14]	[8]	[6]

25. “Yes” or “No” answer to the question “Do you benefit from the national social tariff for electricity?”
26. “Yes” or “No” answer to the question “Do you benefit from the national social tariff for gas?”
27. “Yes” or “No” answer to the question “Do you qualify for the national social tariff for energy?”
28. “Yes” or “No” answer to the question “Do you benefit from the national social tariff for heating oil?”
29. “Yes” or “No” answer to the question “Do you know if you qualify for the national social tariff for energy?”
30. “Yes” or “No” answer to the question “Do you have a heating system in your dwelling?”
31. “Yes” or “No” answer to the question “Do you know what type of heating system you have in your dwelling?”
32. “Yes” or “No” answer to the question “Do you have an individual all-electric heating system in your dwelling (mounted radiators/convectors installed in every room and not inter-connected to a boiler or furnace)?”
33. “Yes” or “No” answer to the question “Do you have an individual central heating system in your dwelling (boiler or other type of central heating)?”
34. “Yes” or “No” answer to the question “Do you have an independent space heater(s) in your dwelling (or independent heating equipment in each room)?”
35. “Yes” or “No” answer to the question “Do you have a communal (or collective) central heating system in your dwelling (communal boiler or heat pump)?”
36. “Yes” or “No” answer to the question “Do you have a mixed heating system in your dwelling (a specific heating system that associates a communal heating system with an individual heating system or a dual (“bi-junction”) electric heating system)?”
37. “Yes” or “No” answer to the question “Do you have another type of heating system in your dwelling?”
38. “Yes” or “No” answer to the question “Do you have a district heating system in your dwelling (or a heat network)?”

Table 3 – Description of profiles of the most representative fuel-poor households in each cluster according to the 10% indicator

	Profile description and weight of the cluster in the total sample			
	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Household characteristics				
[9] Sex of the household reference person (SEXE)	—	Men (86.73%)	Women (66.02%)	Women (77.77%)
[2] Age of the household reference person (AGEPR)	[61-80] (63.42%) >80 (43.05%)	[41-60] (80.95%)	[21-40] (40.66%)	[21-40] (66.67%)
[3] Socio-economic group of the household (PCS2003)	Former tradesmen, shopkeepers or business directors (21.75%)	Administrative assistants (12.24%) Skilled trade worker (trade) (11.22%)	Police officer/Military person- nel (19.61%) Administration and sales pro- fessionals (18.66%)	Supervisor (44.45%)
[10] Disposable income (REVENU DISPONIBLE 2012)	[1e+04,2e+04] (52.77%) [1e+04,2e+04] (52.77%)	[2e+04,3e+04] (42.85%) [3e+04,4e+04] (29.25%)	[1e+04,2e+04] (44.01%) [0,1e+04] (16.26%)	— —
[1][4] Beneficiary of national social tariff for energy (ETSOC)	Do not qualify (52.77%)	Do not know (99.31%)	Do not qualify (81.39%)	Yes, for electricity (88.88%) Yes, for gas (55.56%)
Dwelling characteristics				
[7] Type of dwelling (EHTLC)	Detached house (90.27%)	Detached house (93.53%)	Detached house (37.32%)	—
[8] Surface area of dwelling (EHST)	—	[100-150m ²] (48.29%)	[40-70m ²] (51.67%)	—
[5][6] Type of heating system (EKMOD)	Individual central heating (76.30%), Indep. space heaters (49.07%)	Indep. space heaters (46.25%)	Individual all-electric heating (38.27%) Indep. space heaters (21.05%)	— —
Weight of the cluster in the sample	29.67%	40.38%	28.57%	1.38%

Table 4 – Description of profiles of the most representative fuel-poor households according to the LIHC (m^2) indicator

	Profile description and weight of the cluster in the total sample			
	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Household characteristics				
[1] Age of the household reference person (AGEPR)	[61-80] (47.82%) >80 (17.39%)	[41-60] (64.51%)	[21-40] (48.05%)	<20 (8.10%)
[4] Socio-economic group of the household (PCS2003)	Manager (31.52%)	Shop assistants (17.20%) Skilled trade workers (15.05%)	Police officer/Military personnel (32.46%) Administrative and sales profession- als (16.88%)	Shop assistants (24.32%) Public sector assistant or worker (13.51%)
Dwelling characteristics				
[7] Type of dwelling (EHTLC)	Detached house (91.19%)	—	Apartment (55.84%) Detached house (41.55%)	Apartment (94.59%)
[5] Surface of the dwelling (EHST)	[100-150m ²] (35.86%)	[40-70m ²] (16.12%)	[40-70m ²] (41.55%)	[1-40m ²] (51.35%)

Cf. next page

Table 4 – Continued

	>150m ² (9.78%)			
[6] Tenure type (ESTOC)	Homeowners (75.86%)	Homeowners (51.12%)	Tenants (62.35%)	Tenants (82.35%)
	>150m ² (9.78%)			
[2][3][10] Type of heating system (EKMOD)	Individual (98.27%)	Individual central heating (91.02%) Indep. heaters (24.73%)	Individual electric heating (60.13%) Indep. heaters (24.27%) Individual central heating (31.77%)	Communal central heating (49.64%)
Other variables				
[9] Did you suffer from the cold for at least 24h last winter? (EGCHAUF)	No (94.56%)	—	Yes (58.44%)	—
[8] Type of geographical setting (RP TAILLE UU)	[200000,1999999] (9.89%) Paris (1.71%)	Rural (18.27%)	[200000,1999999] (30.47%)	Paris (49.53%)
Weight of the cluster in the sample	31.43%	30.76%	25.41%	12.40%

Table 5 – Description of profiles of the most representative fuel-poor households in each cluster according to the Thermal Discomfort indicator

	Profile description and weight of the cluster in the total sample		
	Cluster 1	Cluster 2	Cluster 3
Household characteristics			
[1] Age of the household reference person (AGEPR)	<20 (38.03%)	[21-40years] (56.88%)	[41-60years] (70.93%) [61-80years] (18.60%)
[3] Socio-economic group of the household (PCS2003)	Administrative and sales professionals (20.85%)	Farmer G (8.45%) Technicians (7.74%)	Unskilled trade or production workers (63.94%)
Dwelling characteristics			
[2] Type of dwelling (EHTLC)	Apartment (99.38%)	Detached house (78.16%)	Detached house (74.41%)
[8] Surface of dwelling (EHST)	[40-70m ²] (42.33%) [70-100m ²] (38.65%)	[100-150m ²] (29.57%)	—
[4-5] Type of heating system (EKMOD)	Communal central heating (46.01%) Indep. heaters (20.24%)	Individual central heating (66.19%) Indep. heaters (35.91%)	Other (13.95%) ³⁹
[7] Year of dwelling construction (BATI PERIODE)	[1945,1970] (50.92%)	[1945,1970] (24.64%) [1991,2006] (22.53%)	[1945,1970] (15.11%)
Other variables			
[9] Did you suffer from the cold for at least 24h last winter? (ERESTRIC1)	No (72.39%)	Yes (69.71%)	—
[6] Type of geographic setting (RP TAILLE UU)	Paris (34.35%) [200000,1999999] (33.12%)	Rural (33.80%)	Rural (35.80%) [200000,1999999] (13.95%)
Weight of the cluster in the sample	41.68%	36.06%	22.26%

39. This means that households belonging to this cluster use a heating system other than individual central heating (with a boiler or other system), communal central heating (boiler), district heating, individual (built-in) electric heating, mixed (communal and individual), or independent heating equipment.

3.2 Intra-indicator analysis: how profiles of fuel-poor households vary depending on the construction of the indicator

In most cases, fuel poverty has been studied through the narrow use of expenditure-based indicators which are – by construction – based on the definition of exogenous thresholds that lack any theoretical or empirical foundations. In this section, we extend the inter-indicator analysis conducted in previous section by analysing the drawbacks of relying on such exogenous thresholds, particularly in terms of profile variation.

As in section 3.1, we use a data set extracted from the “Phébus” database 2013. To conduct our analysis, we propose a sensitivity analyses based on a logit specification written as follows:

$$\text{Prob}(\text{EP} = 1|X_i) = \alpha + \sum_{i=1}^{13} X_i \quad (4)$$

where X_i represents the i^{th} variable included in the model (*cf.* Table 6). We include both household and dwelling characteristics to better discern differences in fuel-poor profiles. Using other combinations of variables and other models has no impact on our conclusions: in particular, the fuel-poor profiles are highly sensitive to the thresholds chosen. Therefore, slight changes in the threshold change the composition of the population identified as fuel-poor, thus, the target population.

Table 6 – Description of variables included in the logit model

Variable	Description
Isolated women	=1 if the person is a woman and single, 0 otherwise
Isolated elderly people	=1 if the person is older than 59 years and single, 0 otherwise
Rural community	=1 if the town population has less than 2000 inhabitants, 0 otherwise
Thermal discomfort	=1 if the person answered yes to “Egchauff” ^a variable, 0 otherwise
Limited vehicle use	=1 if the person encountered financial difficulties with respect to vehicle use
Energy consumption	= quantitative variable taken from Energy Performance Certificate (kWh/m ²)
Post-1970 building	=1 if dwelling was built after 1970, 0 otherwise
Tenure type	=1 if the person is tenant, 0 if owner
Energy mix gas <i>vs</i> electricity	=1 for gas as heating energy, 0 otherwise
Energy mix oil <i>vs</i> electricity	=1 for oil as heating energy, 0 otherwise
Energy mix other <i>vs</i> electricity	=1 for other energy as heating energy (except electricity), 0 otherwise
Household size	= size of household (cu)
Dwelling size	= size of dwelling (m^2)

a. “Egchauff” variable denotes whether the person answered yes to the question “*Did you suffer from the cold last winter?*”

We note that the choice of the specification, *i.e.* logit, probit, complementary log-log, etc., does not matter here because we did not aim to identify the best econometric model to determine fuel-poor households. Instead, we focused on showing the impact of threshold variation on the identification of the fuel-poor population. In other words, we sought to show how some ranges of indicator thresholds lead to identifying some households as fuel-poor and other ranges clearly exclude them.

We consider two threshold-based expenditure indicators, namely the 10% and the LIHC (m^2). For the 10% indicator, we modified the original exogenous threshold of 10% from 0% to 16%⁴⁰ and examine how it changes the number of households considered as fuel-poor and their characteristics. We used the same methodology with the LIHC (m^2) indicator. We modify the standard threshold of the median of fuel expenditures, *i.e.* fuel expenditures per $m^2 > X$ times national median expenditures per m^2 , to a value ranging from 0.3 to 1.8. Since the LIHC (m^2) depends on a second threshold (*cf.* section 2), *i.e.* equivalised net income $< X$ times equivalised median net income, we also examined the impact of modifying the two thresholds simultaneously⁴¹. To save space and

40. This range of values ensures that a sufficient number of observations are available for the estimation of the model, *i.e.* minimum of 50 observations for $y = 1$ and $y = 0$.

41. To check the quality of our results, we generated various indices of good discrimination of the model, *i.e.* AUC

479 facilitate the presentation of the results, we only report the results (figures) for LIHC (m^2) below⁴².

480

481 *Incidence on the size of fuel-poor population*

482

483 For the 10% indicator, the size of the fuel-poor population depends on the value of the thresh-
484 old. For example, a 20% drop in the threshold from 10% to 8% leads to an increase in the number
485 of fuel-poor households by a factor ranging from 28% to 74%. This result means that the elasticity
486 of the fuel-poor population with regard to the threshold is greater than 1. The same conclusion
487 holds when we consider the LIHC (m^2) indicator. For instance, as shown in Figure 3(a), when
488 we vary the initial median threshold by 20% from 1 to 0.8, the number of fuel-poor decreases by
489 19.4%. By extension, when both thresholds of the LIHC (m^2) indicator are modified, we observe
490 the same type of variation with respect to the size of the fuel-poor population.

491

492 *Island of significance effect*

493

494 In addition to affecting the size of the fuel-poor population, changing the threshold also leads to
495 a modification in its characteristics, or equivalently, the composition of the fuel-poor population.
496 Therefore, it becomes more difficult to define a common profile. In particular, our results show
497 that two effects make it difficult to describe the characteristics of the fuel-poor, namely the “islands
498 of significance effect” and the “switching signs effect”.

499 The “islands of significance effect” relates to the fact that some variables seem to have a signif-
500 icant statistical impact on the probability of being fuel-poor only for a narrow range of threshold
501 values⁴³. For example, as shown in Figures 3(b) and 3(c), a standard analysis using the conven-
502 tional LIHC (m^2) thresholds would lead to the conclusion that the variable “Rural community” is
503 not significantly associated with the probability of being fuel-poor (Figure 3(b)). Conversely, the
504 choice of another nearby range of threshold values may have led to the opposite conclusion. These
505 conclusions also hold when we modified the two thresholds of LIHC (m^2) simultaneously (Figure
506 3(c))⁴⁴. These figures demonstrate the existence of statistically significant areas and statistically
507 non-significant areas for the variable “Rural community”. In particular, there are flat areas and
508 peaks for different variables and for a narrow range of threshold values, indicating a high instability
509 of fuel-poor profiles (*cf.* Appendix D).

510 The second effect, the “switching signs effect”, means that coefficients of variables included in
511 the model change sign when the threshold level changes, *i.e.* from a significantly positive effect to
512 a significantly negative effect or *vice versa*.

513

514 *Incidence on the profiles of fuel-poor households (with an application using the case of the French 515 Energy Voucher)*

516

517 Beyond local effects for one variable (characteristic) due to a change in the threshold, we
518 also observe a general change in fuel-poor profiles. Such effects can be detected both through the
519 optimal size of the model, *i.e.* optimal number of variables, and the type of significant variables (*cf.*
520 Figure 3(d) and Table 7). The optimal dimension of the model refers to the number of variables to

and Brier criteria.

42. Figures associated with the 10% indicator are available upon request. We do not report them to save space. The instability of profiles find for LIHC (m^2) was also observed for the 10% indicator.

43. The value 0 is not included in the confidence intervals.

44. The P-value associated with the probability of the null assumption is that the coefficient of the variable is not significantly different from zero.

521 be included. It is obtained with stepwise selection based on our initial specification (equation 4).
522 This optimal dimension changed greatly when we modified the threshold cut-off (*cf.* Figure 3(d)).

523 For the LIHC (m^2) indicator, changing the threshold from 0.4 to 1.2 times the median equiv-
524 alised net income, results in shows (at least) two important changes in the dimension of the model
525 (Figure 3(d)). The first change is identified at a cut-off of 0.42 times the median income. Then,
526 from a cut-off of 0.42 to 0.66 times the median income, we observe a transitional change where
527 variables describing a fuel-poor person are subject to substantial modifications. Finally, in the
528 last stage, the fuel-poor profiles become stable and can be described with eight main variables,
529 *i.e.* “Rural community”, “Limited vehicle use”, “Energy Consumption”, “Tenant”, “Type of heating
530 system”, “Household size”, “Dwelling size”. Unfortunately, the conventional threshold of 0.6 times
531 the median income is in the middle of one of these cut-offs. An alternative conventional way to
532 display the same conclusion is to report the results in terms of econometric output as shown in
533 Table 7. For illustration, we estimate these changes for the income threshold modification of LIHC
534 (m^2). Although some characteristics remain identically targeted regardless of the threshold chosen
535 (like “Tenants” or “Type of heating system”), other characteristics greatly depend on the choice of
536 threshold. If 0.7 times the median income had been chosen instead of the 0.6 times the median
537 income to determine the fuel-poor population, then “Isolated elderly” people and “Rural commu-
538 nities” would be more likely to be targeted.

539 To display the same result in more concrete terms, we ran the same sensitivity analysis on the
540 threshold applied for the French Energy Voucher. This Voucher corresponds to a new public policy
541 that was launched in France in January 2018 as a measure to fight fuel poverty⁴⁵. The Energy
542 Voucher is attributed to the poorest 15% of households, *i.e.* less than €7700/*cu* per year to help
543 them to pay their energy bill. The determination of this particular group of the population is
544 based on income level and on the size of the household (*cu*)⁴⁵. Results of the sensitivity analysis
545 show that this threshold targets primarily tenants, rural communities, large households, and small
546 pre-1970 dwellings (*cf.* Table 8). However, when modifying this threshold by taking a larger part
547 of poor households, for example 30%, leads other sub-groups of the population, such as isolated
548 elderly people, and other types of dwelling, such as dwellings using other heating systems than
549 electric heating systems. This supports, once again, that the target population depends on the
550 construction of indicators, in particular, on their threshold levels.

551 From a more general point of view, this sensitivity analysis modifying the threshold based on
552 which an Energy Voucher is attributed in France raises the issue of the reliability and relevance of
553 a public policy threshold to target fuel-poor households based on income⁴⁶. Fuel poverty is often
554 associated with income poverty due to the fact that the latter is usually used to capture the mon-
555 etary aspect of fuel poverty. However, although low incomes can drive fuel poverty, fuel poverty
556 also has other determinants such as energy-inefficient buildings and appliances (Boardman, 2012).
557 In addition, from a purely quantitative point of view, even if there is a relationship between fuel
558 poverty and income poverty, this relationship is not always symmetrical and/or significant. There-
559 fore, as described by Palmer et al. (2008), most fuel-poor households are income-poor but most
560 income-poor households are not fuel-poor⁴⁷. Other scholars argue that fuel and income poverty
561 should be considered as independent phenomena⁴⁸. Therefore, even before analysing how chang-

45. <https://www.ecologique-solidaire.gouv.fr/sites/default/files/Rapport%20evaluation%20cheque%20energie.pdf>

46. We are grateful to the anonymous reviewer who suggested developing this point.

47. This statement was empirically validated in a study in Spain, showing that only 28.5% of income-poor are affected by fuel poverty while 79.6% of the fuel-poor are income-poor (Phimister et al., 2015).

48. According to Phimister et al. (2015) and Üрге Vorsatz and Tirado Herrero (2012), there are two reasons for considering fuel and income poverty separately. First, an event can impact one type of poverty without modifying the other. Second, the consequences of fuel poverty are different from those of income poverty in terms of morbidity

562 ing the Energy Voucher threshold affects the profile of French fuel-poor households, targeting the
563 fuel-poor based on income appears to be unwise because it can affect the composition of groups,
564 thus, their profiles.

and mortality, but also in terms of greenhouse gas emissions.

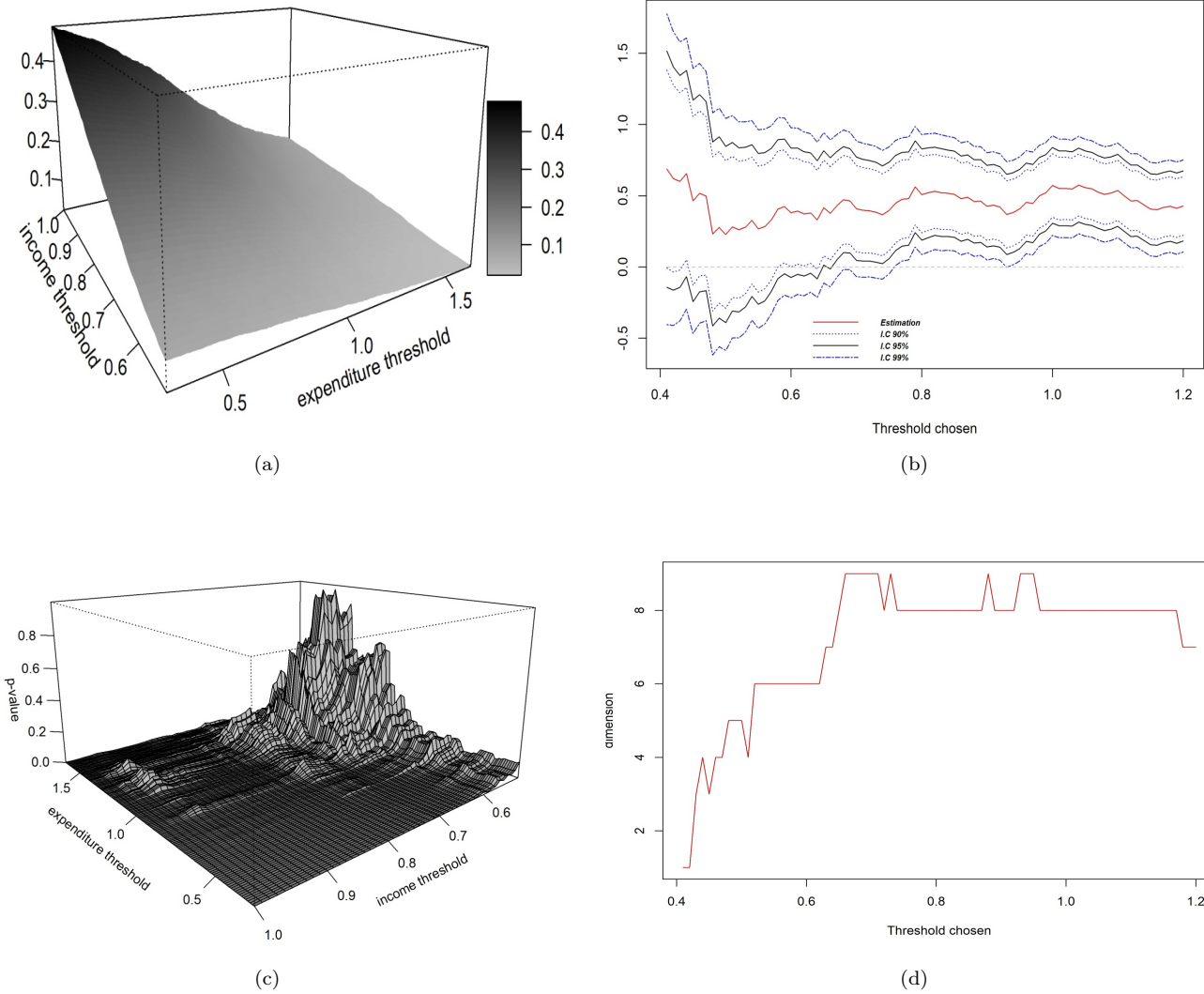


Figure 3. (a) Variation in the number of fuel-poor households (share of population) as a function of the indicator threshold values for the LIHC indicator, (b) Estimation and confidence intervals for the variable "Sex" according to different threshold levels of the LIHC indicator (variation of only one threshold, *i.e.* equivalised income < X times national median income), (c) Statistical significance of the variable "Rural community" in the model according to different values of the two thresholds of the LIHC (m^2) indicator (flat areas under 0.05 denote statistical significance for this variable whereas peaks indicate level of non-significance), (d) Optimal dimension of the model according to different threshold levels of the LIHC (m^2) indicator (variation of only one threshold, *i.e.* equivalised income < X times \times national median income)

Table 7 – Sensitivity analysis (1): variation of fuel-poor profiles according to changes in the LIHC (m^2) income threshold

LIHC (m^2)	Income Threshold				
	0.4xMedian	0.6xMedian	0.7xMedian	0.8xMedian	1xMedian
Intercept	-5.2929 (1.0864)*** ^a	-3.8671 (0.5441)***	-3.1977 (0.4428)***	-2.7761 (0.3943)***	-2.1294 (0.3325)***
Isolated women	-0.3340 (0.8122)	-0.0974 (0.4186)	0.0618 (0.3118)	0.1746 (0.2750)	0.1551 (0.2353)
Isolated elderly people	0.8418 (0.7591)	0.3335 (0.4136)	0.6408 (0.3067)**	0.4762 (0.2743)*	0.5955 (0.2342)**
Rural community	0.3545 (0.4676)	0.3800 (0.2316)	0.4079 (0.1849)**	0.5081 (0.1633)***	0.5718 (0.1356)***
Thermal discomfort	-0.2895 (0.5448)	0.2545 (0.2403)	0.3542 (0.1979)*	0.3102 (0.1811)	0.3151 (0.1621)**
Limited vehicle use	1.3599 (0.4298)***	0.9658 (0.2189)***	0.7950 (0.1891)***	0.7269 (0.1741)***	0.6939 (0.1573)***
Energy consumption (EPC)	-0.0002 (0.0014)	0.0012 (0.0006)**	0.0014 (0.0005)***	0.0014 (0.0004)***	0.0013 (0.0004)***
Post-1970 building	-0.2726 (0.4036)	-0.1729 (0.1962)	-0.2980 (0.1576)*	-0.1562 (0.1385)	-0.1059 (0.1165)
Tenure Type	0.8650 (0.4439)*	0.6821 (0.2150)***	0.7220 (0.1762)***	0.6784 (0.1576)***	0.5387 (0.1393)***
Energy mix gas <i>vs</i> electricity	0.5368 (0.4618)	0.9115 (0.2376)***	0.9247 (0.1941)***	1.1057 (0.1692)***	0.8835 (0.1397)***
Energy mix oil <i>vs</i> electricity	-0.4829 (0.7932)	1.4058 (0.2803)***	1.6872 (0.2235)***	1.6913 (0.2002)***	1.7233 (0.1699)***
Energy mix others <i>vs</i> electricity	1.0018 (0.6916)	1.1898 (0.4031)***	1.4957 (0.3199)***	1.5326 (0.2901)***	1.4466 (0.2592)***
Household size	0.2113 (0.3926)	0.8163 (0.1962)***	0.7109 (0.1656)***	0.7147 (0.1473)***	0.8191 (0.1258)***
Dwelling size	-0.0009 (0.0049)	-0.0175 (0.0036)***	-0.0172 (0.0028)***	-0.0182 (0.0025)***	-0.0178 (0.0020)***
Observations	2076	2076	2076	2076	2076
Brier	0.013	0.056	0.085	0.109	0.155
AUC	0.717	0.797	0.792	0.781	0.768

a. *** significant at $P < 1\%$, ** 5% or * 10%.

Table 8 – Sensitivity analysis (2): probability of qualifying for the French Energy Voucher programme according to the equivalised income threshold

Threshold (share of the poorest population)	Income/cu						
	0.05	0.1	0.15	0.2	0.25	0.3	0.35
Intercept	-4.8188 (0.6904)*** ^a	-4.1180 (0.4975)***	-3.2365 (0.4075)***	-2.7629 (0.3638)***	-2.5610 (0.3351)***	-2.1868 (0.3198)***	-1.9679 (0.3060)***
Isolated women	0.6569 (0.5494)	0.2255 (0.3847)	0.5208 (0.3018)*	0.4229 (0.2631)	0.3917 (0.2418)	0.4380 (0.2270)*	0.3621 (0.2181)*
Isolated elderly people	0.4495 (0.5699)	0.6777 (0.3812)*	0.2152 (0.3133)	0.5199 (0.2665)*	0.4728 (0.2441)*	0.5294 (0.2288)**	0.6304 (0.2187)***
Rural community	0.4597 (0.2991)	0.5656 (0.2071)***	0.4251 (0.1701)**	0.4704 (0.1509)***	0.4541 (0.1384)***	0.5614 (0.1309)***	0.4441 (0.1250)***
Thermal discomfort	0.2401 (0.3164)	0.2225 (0.2257)	0.2291 (0.1885)	0.4337 (0.1689)**	0.2505 (0.1625)	0.2994 (0.1584)*	0.2134 (0.1568) (0.1568)
Limited vehicle use	0.7910 (0.2835)***	0.8797 (0.2012)***	1.0467 (0.1683)***	0.8606 (0.1585)***	0.7780 (0.1533)***	0.9578 (0.1511)***	1.0814 (0.1523)***
Energy consumption	-0.0001 (0.0009)	0.0008 (0.0006)	0.0005 (0.0005)	0.0001 (0.0004)	0.0005 (0.0004)	0.0004 (0.0004)	0.0005 (0.0004)
Post-1970 building	-0.4323 (0.2556)*	-0.2044 (0.1803)	-0.4190 (0.1464)***	-0.3648 (0.1298)***	-0.3118 (0.1191)***	-0.2196 (0.1132)*	-0.2260 (0.1083)**
Tenure Type	0.5540 (0.2854)*	0.7137 (0.1992)***	0.7580 (0.1648)***	0.8283 (0.1484)***	0.9646 (0.1386)***	0.9693 (0.1348)***	0.9892 (0.1330)***
Energy mix gas vs electricity	0.3175 (0.2841)	0.3123 (0.2100)	0.2500 (0.1705)	0.2936 (0.1511)*	0.3265 (0.1385)**	0.3607 (0.1320)***	0.2527 (0.1258)**
Energy mix oil vs electricity	-0.8323 (0.5518)	0.1049 (0.2905)	0.0621 (0.2348)	0.2716 (0.1999)	0.2326 (0.1837)	0.4014 (0.1707)**	0.3780 (0.1620)**
Energy mix other vs electricity	0.1656 (0.5662)	0.1494 (0.4173)	0.3091 (0.3277)	0.2740 (0.3000)	0.4479 (0.2716)*	0.5176 (0.2608)**	0.4408 (0.2544)*
Household size	1.1392 (0.2354)***	1.1606 (0.1778)***	0.9781 (0.1489)***	0.9789 (0.1347)***	0.9040 (0.1253)***	0.8728 (0.1208)***	0.8931 (0.1165)***
Dwelling size	-0.0095 (0.0043)**	-0.0138 (0.0032)***	-0.0107 (0.0024)***	-0.0111 (0.0021)***	-0.0099 (0.0018)***	-0.0113 (0.0018)***	-0.0106 (0.0016)***
Observations	2076	2076	2076	2076	2076	2076	2076
Brier	0.032	0.065	0.099	0.126	0.150	0.167	0.182
AUC	0.735	0.757	0.748	0.740	0.732	0.740	0.737

a. ***significant at $P < 1\%$, ** $P < 5\%$ or * $P < 10\%$.

565 4 Discussion and recommendations

566 Our results demonstrate how the determination of the fuel-poor population depends on the
567 choice of the fuel poverty indicator and its construction (threshold). Results from different indi-
568 cators can be different or even conflicting, *i.e.* a person identified as fuel-poor according to one
569 indicator, may not be according to another. Although this issue has been already raised in the
570 literature, it remains unresolved and even unmeasured in the majority of studies. However, this
571 issue greatly affects the determination of the magnitude of fuel poverty as well as the fuel-poor
572 profiles, and calls into question the effectiveness of identifying fuel-poor households and of policies
573 aiming to fight fuel poverty. The widespread use of indicators with no theoretical foundation paves
574 the way to using a given indicator or threshold to favour a particular fuel-poor profile. Given
575 that we have revealed the empirical importance of the issue, we argue that new methodologies are
576 needed to overcome the limits of conventional indicators, thus to measure fuel poverty in a more
577 effective way. Below, we give some recommendations.

578

579 *Combining conventional indicators with a sensitivity analysis*

580

581 When aiming to determine the fuel-poor population and analyse its profile, several types of
582 conventional indicators can be used. For example, to measure the extent and composition of fuel
583 poverty in France, Legendre and Ricci (2015) use three objective indicators, namely the 10%, the
584 AFCP and the LIHC. They conclude that the share of fuel-poor households and their charac-
585 teristics differ significantly depending on which indicator they use. More recently, Papada and
586 Kaliampakos (2016) combined the objective 10% indicator with subjective indicators to measure
587 fuel poverty in Greece. This combined approach should be generalised. In this context, in France,
588 the French National Observatory of Fuel Poverty suggests using two approaches to measure fuel
589 poverty (ONPE, 2016). The first one is based on the combined use of three objective expenditure
590 indicators, *i.e.* the 10%, LIHC (*cu*) and LIHC (*m*²) indicators, and the second is based on the
591 subjective Thermal Discomfort indicator.

592 Although results of several indicators can differ, comparing them helps to analyse in detail the
593 characteristics of fuel-poor households. One way to ensure results of combined conventional indica-
594 tors is to associate each indicator outcome with a sensitivity analysis. The aim is to highlight how
595 results change depending on the type of indicator or on its construction, *i.e.* threshold level. This
596 approach leads to a reliable identification process, based on which the necessary policies targeting
597 the elimination of fuel poverty can be implemented (Dubois, 2012).

598

599 *Alternative use of threshold-based indicators*

600

601 Another way to deal with the variation in the profiles of the fuel-poor when using conventional
602 threshold-based indicators is to use them without the thresholds. For instance, the evolution of
603 fuel poverty can be tracked using the median of the fuel-poverty ratio as well as the skewness
604 and kurtosis of its distribution. As shown in Figure 4, a shift in the median value can indicate a
605 worsening situation whereas a shift in the symmetry of the curve can suggest an improvement with
606 less inequality. Conversely, the skewness of the distribution can indicate a worsening situation for
607 the most exposed fuel-poor. Obviously, these indicators do not provide any head counts of the
608 fuel-poor population and cannot quantitatively analyse the spread of the phenomenon. Neverthe-
609 less, they give an interesting complementary overview of the temporal dynamics of fuel poverty.

610

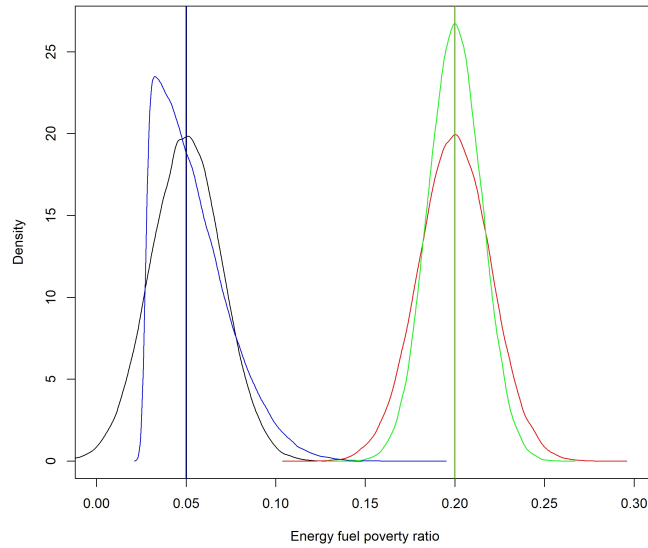


Figure 4. Alternative way of examining expenditure-based indicators: evolution of the distribution of the 10% indicator Note: An arbitrary threshold is not necessarily required to analyse the dynamics of fuel poverty. Distribution shifts and asymmetry of the fuel-poor population can represent an unbiased exploratory means to consider the issue.

611 *Using new types of indicator*

612

613 Given that there is currently no commonly accepted approach to measure fuel poverty, sev-
 614 eral recent studies have proposed tackling the issue by constructing new types of indicator(s). In
 615 this context, in addition to measuring fuel poverty by using the most common subjective indica-
 616 tors, *i.e.* arrears on utility bills, inability to keep the home adequately warm and the presence
 617 of damp walls and leaks, Papada and Kaliampakos (2016) constructed new indicators focusing on
 618 health problems caused by poor heating conditions and restriction of other essential needs such as
 619 food or clothing (essential for meeting energy needs).

620 In a more general framework, other studies call for the construction of indicators, so-called
 621 composite indices, taking into account the multidimensional nature of fuel poverty. In particular,
 622 Okushima (2017) constructed a multidimensional energy poverty index (MEPI) that considers three
 623 attributes of fuel poverty, namely energy costs, income and dwelling energy efficiency. Similarly,
 624 Charlier and Legendre (2016) built an index that takes into account household heating restrictions
 625 in addition to monetary constraints and dwelling energy efficiency.

626 By extension, some recent studies based on energy deprivation, a concept commonly applied
 627 to developing countries, call for the revision the conceptual framework that form the basis for the
 628 construction of the conventional indicators of fuel poverty in developed countries. In particular,
 629 they advocate the definition and the use of indicators coming from the energy capabilities frame-
 630 work (Sen (1992), Nussbaumer et al. (2003), Nussbaumer et al. (2012)). This framework is based
 631 on the argument that the energy demand is not for energy per se, but for the services energy use
 632 can provide such as lighting, cooking, heating and cooling. Therefore, Smith and Seward (2009)
 633 distinguish between basic and secondary capabilities⁴⁹. Day et al. (2016) apply this capabilities
 634 approach to argue why energy is used and needed and to propose a innovative multidimensional

49. Basic capabilities are those that can be defined in broad and generic forms and are considered as the most fundamental, for example education, bodily health and social respect. Secondary capabilities are rather seen as component parts of materialising basic capabilities such as having access to information, using machinery and preparing food.

635 definition of energy poverty that integrates approaches to energy poverty from global North and
636 South contexts. They argue that the energy capabilities framework identifies several areas of inter-
637 vention to address the problem of energy poverty, in particular, the energy poverty in the context
638 of climate change.

639 5 Conclusion

640 During the last decade, the literature on fuel poverty has gained growing interest. Although
641 it has offered and applied many objective and subjective indicators to measure fuel poverty, it
642 has failed to reach a consensus on the appropriate indicator to use to reliably identify affected
643 households and implement appropriate public policies to help them to overcome the problem.
644 Clearly, there is a trend in the use of indicators, such as for example the increasing use of the
645 10% indicator after its official use by the UK government in 2001. Similarly, the LIHC indicator
646 has been well received since its first appearance in Hills (2011, 2012) reports. Nonetheless, several
647 discursive criticisms related to the use of these indicators have been extensively relayed in the past
648 few years. Although many are valid, they clearly lack empirical support.

649 The aim of this study was to fill this theoretical-empirical gap. In particular, based on a critical
650 review of the literature on fuel poverty indicators, we focused on two issues. First, because fuel
651 poverty indicators have neither real theoretical foundations nor any empirical consensus as to the
652 identification of the fuel-poor, we investigated how the use of one indicator over another can lead to
653 the exclusion of some part of the affected population from being targeted by public policy measures
654 devoted to fighting the problem. Further, in the case of exclusion, we sought to determine which
655 trade-off is at work and how it is applied, *i.e.* type of indicator and/or its threshold. Second,
656 we examined the associated crucial question of the homogeneity of the profiles of the fuel-poor
657 population and its impact on the implementation, the reliability and the relevance of public policy
658 targeting. To address these issues, we analysed in detail the impact of the choice of indicators on
659 the identification of the fuel-poor population, in particular, on their profile description.

660 Our results show that the profile of the fuel-poor depends on the indicator selected and on its
661 construction, *i.e.* threshold level in the case of expenditure indicators. In particular, the inter-
662 indicator analysis based on an HCA showed that the fuel-poor population determined with a given
663 indicator pools several types of profile and that profile groups can differ across indicators. We
664 then detailed the characteristics of some selected representative fuel-poor households. Similarly,
665 the intra-indicator analysis showed that profiles of the fuel-poor as well as the size of groups, or
666 equivalently, the magnitude of fuel poverty has high elasticity for the level of the threshold. In this
667 context, by focusing on the French Energy Voucher as a policy to fight fuel poverty, we also showed
668 how the targeted fuel-poor population changes when changing the policy threshold currently set
669 in France at the poorest 15% of households. Based on these results, we highlight the difficulty
670 of identifying and defining a “*typical profile*” of a fuel-poor household for the implementation of
671 public policies.

672 We argue that both scholars and policy-makers should be aware of the potential trade-offs
673 involved in the use of a given indicator or a given threshold. Some indicators or thresholds favour
674 some groups of population and exclude others. We recommend employing different strategies
675 to deal with these issues, namely the combined use of conventional indicators associated with a
676 sensitivity analysis, the omission of thresholds from expenditure-based indicators, and the use of
677 new types of indicator based on a more suitable conceptual framework. Obviously, these strategies
678 are not mutually exclusive and can be carried out together.

679 The difficulty of identifying the fuel-poor population reveals that there are still a lot of things

680 to learn about fuel poverty. There are in particular three main fields of research to be explored.
681 First, because fuel poverty is basically a dynamic phenomenon, analysing this question can help
682 understand its duration as a function of the profiles of affected groups. Interestingly, it can also
683 help analyse the effectiveness and enforcement of policies to combat fuel poverty. Second, there is a
684 need to better understand the drivers of fuel poverty by distinguishing exogenous and endogenous
685 determinants to identify the most interesting levers that can help overcome the problem. Last,
686 but not least, studies dealing with the relationship between fuel poverty and other poverty-related
687 concepts such as monetary poverty, health, education and social exclusion, should be conducted.
688 The analysis of interactions between these different issues may reveal causal and cumulative effects
689 necessary to understand and, thus, to eliminate fuel poverty.

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696 *de l’Energie*” (CFE)).

697 All remaining errors remain with the authors. The usual disclaimer applies.

698 **A** Brief literature review on fuel poverty indicators, their advantages and their drawbacks

Table A.1 – Brief literature review on fuel poverty indicators, their advantages and their drawbacks

Main references	Definition	Advantages	Drawbacks
1. Objective factual indicators			
----- Expenditure-based indicators -----			
UK Government based on Boardman (1991)	<p>The 10% indicator:</p> <ul style="list-style-type: none"> — Calculation : $I = \frac{\text{Theoretical fuel costs}}{\text{Equalised income before housing costs}}$ — Rule: <ul style="list-style-type: none"> — if $I \geq 10\% \Rightarrow$ the household is fuel-poor, — if $I < 10\% \Rightarrow$ the household is not fuel-poor, 	<ul style="list-style-type: none"> — The comparison between theoretical and actual energy consumption takes into account self-imposed under-heating. 	<ul style="list-style-type: none"> — Based on an obsolete UK energy expenditures threshold going back to 1988, — Based on theoretical rather than actual energy expenditures, — Does not take into account heating restriction practices, — Does not take into account the income level of affluent households, — Does not take into account restricted expenditures.
Hills (2011)	<p>The After Fuel Cost Poverty (AFCP) indicator:</p> <p>Fuel poverty if [Equalised (Income – Housing costs – Domestic fuel costs)] < [60% Equalised (Median income – Housing costs – Domestic fuel costs)]</p>	<ul style="list-style-type: none"> — Taking into account some constrained expenditures, <i>i.e.</i> housing costs, — Identification of the aggravating effect of fuel poverty on monetary poverty. 	<ul style="list-style-type: none"> — Plausible misleading classification of households with very low income as fuel-poor regardless of their fuel needs, — Possible confusion between fuel and monetary poverty.
Hills (2011, 2012)	<p>The Low Income High Costs (LIHC) indicator:</p> <p>Fuel poverty if [Equalised net income < 60% (Equalised median net income)] and Equalised fuel expenditures \geq Required national median fuel expenditures</p>	<ul style="list-style-type: none"> — Definition of two thresholds that distinguish fuel from monetary poverty to ensure reliable identification of fuel-poor households. 	<ul style="list-style-type: none"> — Not based on the constrained income, — Does not take into account heating restriction behaviour practised in some households.
----- The restriction behaviour indicators -----			

cf. next page

Table A.1 – Continued

Main references	Definition	Advantages	Drawbacks
ONPES cited in Dutreix et al. (2014) and ONPE (2014)	The restriction behavior indicator: Theoretical fuel consumption – Actual fuel consumption	– Helps target households that have a cost analysis suitable for dwelling fuel investment.	– Theoretical energy expenditures are usually difficult to assess.
----- Consensual social indicators -----			
Also <i>cf.</i> summary of Healy and Clinch (2002) and Nussbaumer et al. (2012) presented in the section entitled “Composite indices” in this table)			
Healy and Clinch (2002) and Nussbaumer et al. (2012)	Possibility of using different objective indicators: – Presence of damp walls and/or floors, – Lack of central heating, – Presence of rotten window frames, – Access to electricity distribution, – Household appliance ownership.	– Captures multidimensional nature of fuel poverty especially when included in composite indices.	– Possible irrelevant results if used irrespective of other objective indicators.
----- 2. Subjective self-reported indicators -----			
Healy (2003), EPEE (2006), and INSEE ENL (2006)	Possibility of asking different questions: – Do you suffer from thermal discomfort? – Have you experienced difficulty in paying utility bills (in the past)? – Can you afford your energy bills? – Are you satisfied with your heating equipment?	– Can be supplemented with qualitative surveys/interviews to better understand the characteristics of fuel-poor households.	– Results should be interpreted with caution, – Possible contrasting results compared with those of objective indicators mainly with respect to the identification of fuel-poor households.
----- 3. Composite indices ⁵⁰ -----			
Healy and Clinch (2002)	Composite weighted index based on the combination of six consensual social indicators which: – Are split into two sub-groups: subjective self-reported and objective factual indicators, – Pertains to household finances (fuel and utility bills), the state of the building structure (presence of damp or rot), and the dwelling’s heating system.	– Associates objective and subjective criteria, – Suitable for cross-country comparisons.	– Assignments of weights to each indicator incorporated in the composite indice is somewhat arbitrary, – Results vary depending on the weight assigned to each indicator.

cf. next page

50. References cited in this part of the table present indices that were constructed for developed countries. Therefore, if applied to a developing country, some refinements will be necessary, especially with regard to the definition of the dimensions of poverty. In fact, when considering energy poverty in developing countries, most existing studies focus on the question of energy access, not on thermal comfort as in developed countries.

Table A.1 – Continued

Main references	Definition	Advantages	Drawbacks
Thomson and Snell (2013)	Composite weighted index based on the combination of three proxy indicators, namely the presence of arrears on utility bills in last 12 months, the presence of a leaking roof, damp walls or rotten windows and the ability to pay to keep the home adequately warm.	<ul style="list-style-type: none"> — Suitable for cross-country comparisons. 	<ul style="list-style-type: none"> — Assignments of weights to each proxy indicator is somewhat arbitrary, — Results vary depending on the weight assigned to each indicator.
Fabbri (2015)	Composite index, the so-called Building Fuel Poverty Index (BFP), aims to assess the relationship between building energy performance, dwelling habits and fuel poverty.	<ul style="list-style-type: none"> — Focusing on the role of dwelling energy efficiency as a driver of fuel poverty, — the index identifies subjects that can afford to pay for building energy refurbishment. 	<ul style="list-style-type: none"> — Not generally easy to apply in countries other than Italy.
Okushima (2017)	Composite index, the so-called Multidimensional Energy Poverty Index (MEPI), which is composed of three attributes of energy poverty, namely energy costs, income and dwelling energy efficiency.	<ul style="list-style-type: none"> — Considers the multidimensional nature of energy poverty which matches the original concept of energy poverty by Boardman (1991). 	<ul style="list-style-type: none"> — Does not take into account the subjective dimension of fuel poverty.

699 B Details on the computation of fuel poverty rates

700 We start by giving below the list of variables (with their acronyms) that we extract from
701 “Phébus” database to calculate fuel poverty rates. Then we explain how we calculate fuel poverty
702 rates according to the 10%, LIHC, and the Thermal Discomfort indicators.

- 703 — Variables used to calculate fuel costs:
 - 704
 - 705 — “MONTANT ELEC 2012”: annual amount of electricity
 - 706 — “MONTANT GAZ 2012”: annual amount of gas expenditures
 - 707 — “MONTANT FIOUL 2012”: annual amount of heating oil expenditures
 - 708 — “MONTANT GPLC 2012”: annual amount of LPG (tank) expenditures
 - 709 — “MONTANT CHARBON 2012”: annual amount of coal expenditures
 - 710 — “MONTANT BOIS 2012”: annual amount of wood expenditures
 - 711 — “MONTANT GPLB 2012”: annual amount of LPG (bottle) expenditures
 - 712 — “MONTANT PK 2012”: annual amount of odourless kerosene or paraffin expenditures
 - 713
- 714 — Variables used to calculate the equivalised net income:
 - 715
 - 716 — “REVENU DISPONIBLE 2012”: disposal income
 - 717 — “EPMDR2”: amount of mortgage taken out to pay for the purchase of the dwelling (for
718 homeowners)
 - 719 — “EFAMR”: amount of financial support (for homeowners - to be included when calcu-
720 lating housing costs)
 - 721 — “ELLD”: rent (for tenants)
 - 722 — “ELAMR”: amount of financial support (for tenants - to be included when calculating
723 housing costs)
 - 724 — “UC”: number of household consumption units
 - 725 — “EHST”: the surface area of the dwelling.
 - 726
- 727 — Variables used to detect subjective thermal discomfort (feeling cold) at home indoors and
728 the reason for the inability to heat dwelling to a suitable level of warmth:
 - 729
 - 730 — “EGCHAUF: *Did you suffer from the cold for at least 24 hours in your home last win-
731 ter?*”?
 - 732 — “ETDIFF: *Have you encountered financial difficulties in paying your energy bills during
733 the pas two years?*”.
 - 734

735 Given this list of variables, we present below how we identified fuel-poor households with each
736 indicator. Our initial data set was composed of 5405 households.

737 B.1 Determination of fuel-poor households according to the 10% indi- 738 cator

739 Based on Section 2, we calculated the 10% indicator, I, using the following formula:

$$I = \frac{\text{(Actual) Fuel costs}}{\text{Equalised disposable income (before housing costs)}} \quad (\text{B.1})$$

- 740 — if $I \geq 10\% \Rightarrow$ the household is fuel-poor.
 741 — if $I < 10\% \Rightarrow$ the household is not fuel-poor.

742

743 As discussed in Section 2, one drawback of the 10% indicator is that it over-estimates the extent
 744 of fuel poverty within the general population by including households with a high level of income.
 745 To deal with this criticism, the ONPE (2014, 2015) studies suggest including in the calculation
 746 only those households having an income (cu) lower than the threshold of the third decile of income
 747 (cu).

748 Therefore, in our study, households were first sorted according to their income (cu) and then
 749 divided into 10 equal groups each one containing 10% of the global population to create deciles.
 750 Then, the annual threshold of the third income (cu) decile was determined. Only households
 751 having an income (cu) level lower than this threshold were considered as fuel-poor. To consolidate
 752 our calculation, we compared our threshold with national thresholds. In particular, Table B.1
 753 below presents thresholds of the third income (cu) decile that we calculated for 2012 in comparison
 754 with the national 2011, 2012, and 2013 thresholds calculated by the French National Institute of
 755 Statistics and Economic Studies (INSEE) (2014)⁵¹.

Thus, a household is fuel-poor if:

Table B.1 – Threshold of the third decile of income (cu)

Year	“Phébus” threshold	National threshold ^a
2011	—	€16 920
2012	€16 235.20	€16 850
2013	—	€16 930

^a. We note that these thresholds do not represent the exact value of national threshold of the third decile of income (cu) but rather the standard of living of population having an income level situated between the national third and fourth deciles of income.

756

$$\frac{\text{(Actual) Fuel costs}}{\text{Equalised disposable income}} \geq 10\% \quad (\text{B.2})$$

757 and

$$\text{Equalised disposable income } (cu) = \frac{\text{Disposable income}}{\text{Number of consumption unities}} \quad (\text{B.3})$$

$$< \text{Threshold of the third decile of income}$$

758 Our results show that 14.16% of households in our initial sample are fuel-poor according the
 759 10% indicator, *i.e.* 766 of 5405 households.

760 B.2 Determination of fuel-poor households according to the LIHC indi- 761 cator

Based on Section 2, we calculated the LIHC indicator according the following formula:

$$\left\{ \begin{array}{l} \text{Equalised net income} \leq 60\% \text{ (Equalised median net income)} \\ \text{Equalised fuel expenditures} \geq \text{Required national median fuel expenditures} \end{array} \right. \quad (\text{B.4})$$

51. <https://www.insee.fr/fr/statistiques/2417897>. Accessed in July 20, 2017.

762 Equalised fuel expenditures are calculated by dividing fuel expenditures by the number of
 763 consumption units in the case of the LIHC (cu) indicator and by the surface area of the dwelling
 764 in the case of the LIHC (m^2) indicator:

765 — LIHC (cu) indicator:

$$\text{Equalised fuel expenditures } (cu) = \frac{\text{Fuel expenditures}}{\text{Number of consumption units}} \quad (\text{B.5})$$

766 — LIHC (m^2) indicator:

$$\text{Equalised fuel expenditures } (m^2) = \frac{\text{Fuel expenditures}}{\text{Surface}} \quad (\text{B.6})$$

767 Equalised net income is calculated as follows:

$$\text{Equalised net income } (cu) = \frac{\text{Disposable income} - \text{Housing costs} - \text{Domestic fuel costs}}{\text{Number of consumption units}} \quad (\text{B.7})$$

768 In our sample, the value of 60% of equivalised median net income is equal to €12,151.2 and
 769 values of the equivalised median fuel expenditures in the case of LIHC (cu) and LIHC (m^2) are
 770 respectively equal to €841 and €14.64.

771 Our results show that 10.95% of households in our initial sample are fuel-poor according the
 772 LIHC (m^2) indicator, *i.e.* 592 of 5405 households and 9.52% according to the LIHC (cu) indicator,
 773 *i.e.* 514 of 5405 households.

774 **B.3 Determination of fuel-poor households according to the Thermal** 775 **Discomfort indicator**

776 Following the approach of ONPE (2016), a household is fuel-poor according to this subjective
 777 indicator if it satisfies two conditions:

778 — *Condition 1*: a household declares feeling cold because of at least one of the first five reasons
 779 which are considered to be the most representative of a fuel poverty situation, namely:

- 782 1. Insufficient heating system,
- 783 2. Breakdown of heating system,
- 784 3. Poor insulation,
- 785 4. Household heating restriction due to financial burden,
- 786 5. Energy supply cut-off due to unpaid bills,
- 787 6. Improper adjustment or late start-up of the heating system,
- 788 7. Other reasons.

789 — *Condition 2*: a household has an income level less than or equal to the third decile.
 790

791 Depending on data available in “Phébus”, we consider that a household is fuel-poor if it answers
 792 “Yes” to the following two questions related to *Condition 1*:
 793

794 — “Did you suffer from the cold for at least 24 hours in your home last winter?”
 795

796 — “*Have you encountered financial difficulties in paying your energy bills?*”.

797

798 After that, to satisfy *Condition 2*, we selected only those households having an income level less
799 than or equal to the third decile.

800 Our calculations show that 7.75%, thus, 419 of the initial 5045 households are fuel-poor.

801 **C Potential drivers of fuel poverty: summary of the litera-**
 802 **ture**

Table C.1 – Potential drivers of fuel poverty: summary of the literature. Based on Bennett et al. (2002), Scott et al. (2008), Healy (2003), Healy and Clinch (2004), Palmer et al. (2008), Fahmy et al. (2011), Nicolas et al. (2012), Thomson and Snell (2013), Mayer et al. (2014), Waddams Price et al. (2012), Legendre and Ricci (2015), Charlier et al. (2015), Roberts et al. (2015), Fabbri (2015), Ambrosio et al. (2015), and Hache et al. (2017).

Drivers	Expected effect
<hr/>	
Household characteristics	
-Type of household/Marital status, <i>i.e.</i> Single; Widowed; Divorced; Childless couple; Couple with child(ren); Single-parent family.	Single, widowed and divorced persons have a higher risk of being fuel-poor.
-Size of household/Number and age of children	The presence of children increases energy needs, thus, the probability of falling into fuel poverty.
- Sex	Women, mainly single, with dependent children, and unemployed are usually fuel-poor.
- Age	Elderly people seem to be more vulnerable (higher energy needs) and more likely to fall into fuel poverty due to lower incomes.
- Socio-economic group	Belonging to a high socio-economic group reduces the risk of being fuel-poor because it increases the probability of having a high income level.
- Income level, <i>i.e.</i> > or < poverty threshold	A high income level reduces the risk of being fuel vulnerable because it ensures the ability to afford energy ⁵² .
- Employment status	Employment ensures income, thus the ability to afford energy and reduces the risk of falling into fuel poverty. Conversely, students, unemployed workers and retirees have lower income thus higher likelihood of falling into fuel poverty.
- Education level	High educational level reduces the risk of being a fuel-poor because it increases the probability of being employed and having a high income.
- Dwelling occupancy status	Homeowners are less frequently fuel-poor, likely because they have higher income and ensure energy efficiency of their home.
- Daily occupancy of disabled and sick persons in dwelling	Disabled and sick persons have higher probability of being fuel-poor due to more time spent at home, and thereby higher energy needs.
<hr/>	
Dwelling attributes	
- Type of dwelling, <i>i.e.</i> Apartment; Detached dwelling, etc.	The fuel poverty risk increases when the household is living in a detached dwelling.
- Construction date	In France, the first regulations on thermal efficiency came into effect in 1974. Dwellings built after this date are more energy efficient, which may decrease the fuel poverty risk for people living in them.
- Housing surface	Living in a large dwelling increases the probability of becoming fuel-poor because energy needs are higher.
- Heating system	Individual boiler, wood stove or coal stove are usually associated with a high probability of being fuel-poor.
- Heating energy source	High energy prices increase the risk of being fuel-poor.
- Inefficiency of lighting and others electric appliances	Lighting and other electric appliances account for an increasing share of residential energy consumption (10-20%), thus the multiplication and poor energy efficiency of these appliances can lead to high energy needs.
- Energy efficiency	Living in an energy inefficient dwelling increases the consumption of energy and thereby the probability of falling into fuel poverty.
- Other dwelling attributes, <i>i.e.</i> Dampness, leaks, ventilation system, poor lighting, etc.	The presence of dampness, leaks or a broken ventilation system usually exacerbate a pre-existing fuel poverty situation.
<hr/>	
Other drivers	

cf. next page

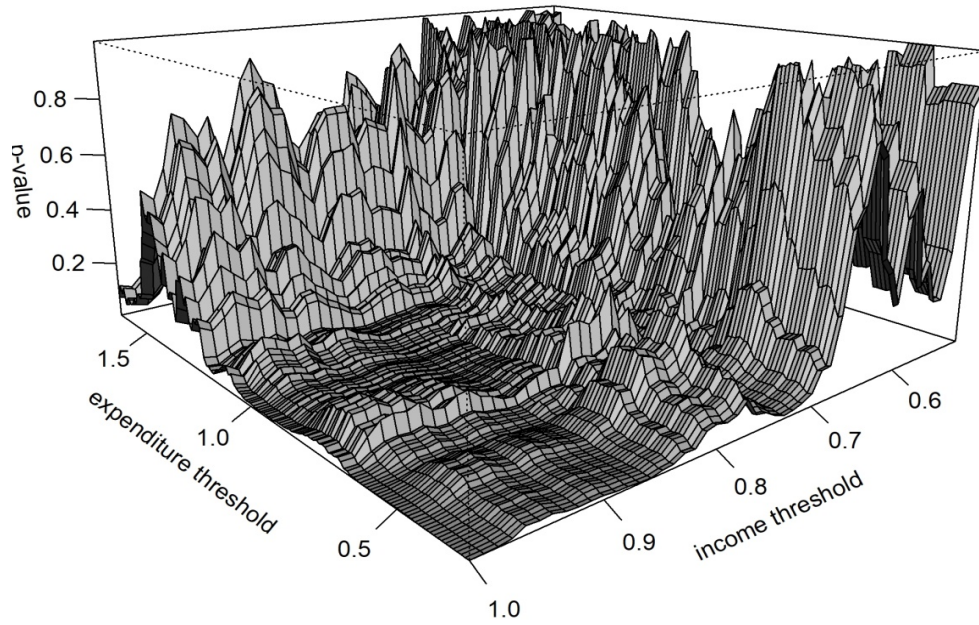
⁵². Regardless the objective income level, there is a subjective dimension in the household's own perception of its financial endowment and quality of life. This perception can affect the amount it decides to devote to satisfy its energy needs.

Table C.1 – Continued

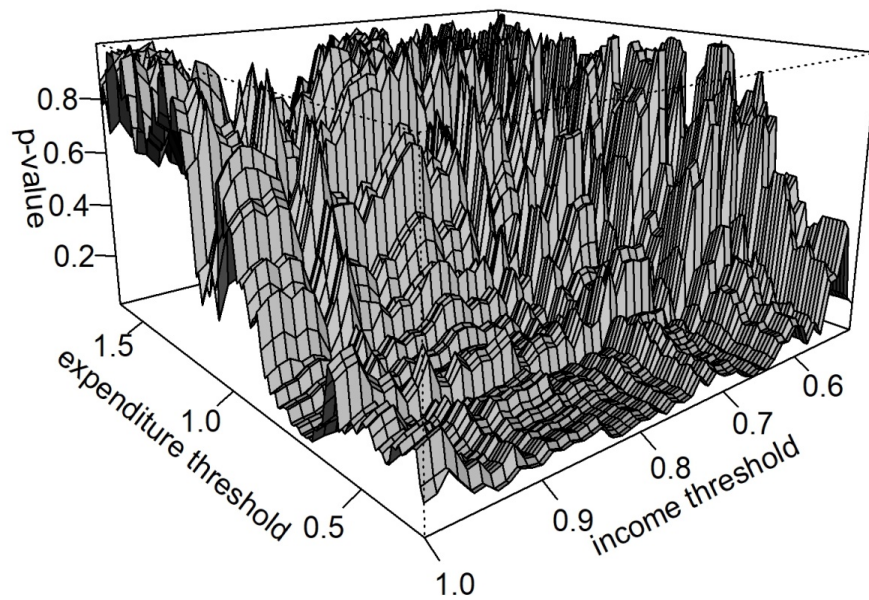
Drivers	Expected effect
- Type of energy payments, <i>i.e.</i> Standard payment versus pre-payment meters	People paying with pre-payment meters are charged a higher price of energy, thereby increasing the risk of falling into fuel poverty.
- Climate characteristics, <i>i.e.</i> Mediterranean; Continental; Oceanic; Temperate.	Living in a hot region decreases heating needs and, therefore, the risk of being fuel-poor ⁵³ .
- Vehicle ownership	Owning a vehicle increases the probability of being fuel-poor because of commute expenditures.
- Geographic location/ rural/ low urbanisation level	It seems that people living in rural areas have a higher risk of falling into fuel poverty because they do not have good access to cheap energy sources (natural gas) or competitive markets. In addition, the supply of real estate market is less important and diversified.

⁵³. Conversely, we note that energy needs can be high in a hot region due to the use of an air-conditioning system (*cf.* Fouquau and Bessec (2008)).

803 D Complementary figures for the intra-indicator analysis (sec-
804 tion 3.2)



(a)



(b)

Figure D.1. (a) A Statistical significance of the variable "Isolated elderly people" in the model according to different values of the two thresholds of the LIHC (m^2) indicator, (b) B Statistical significance of the variable "Isolated women" in the model according to different values of the two thresholds of the LIHC (m^2) indicator.

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