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Fuel Poverty: a Composite Index Approach

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Abstract

Fuel poverty is an increasingly serious problem across countries. However, fuel poverty is not well defined and measured. Today, fuel poverty objective measure which takes into account monetary constraint, bad energy efficiency of the dwelling and heating restriction does not exist. Fuel poverty has been mainly treated as a problem of monetary poverty. However households concerned by a fuel poverty issue are not exactly the same than those concerned by monetary problems. Thus, in this paper, we provide the first Fuel Poverty Index (FPI) taking into account all dimensions of the definition. This index is calculated using objective measures such as (i) the disposable income to consider the monetary constraint, (ii) the energy consumption as a measure of energy efficiency and (iii) the indoor temperature in order to capture heating restriction. Using a matching estimation, the quality of the indoor temperature as a proxy of heating restriction is demonstrated.

Keywords: Fuel Poverty, Matching method, Composite Indicators, Heating restriction, Energy Efficiency.

JEL codes: Q41, Q48, Q58, C21, C61

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1. Introduction

Fuel poverty occurs when a household is unable to afford the most basic levels of energy for adequate heating, cooking, lighting and use of appliances in the home. In 2011, 9.8% of households in EU27 and 15.8% of households in the 12 new Member States could not afford to heat their home adequately (The EU Statistics on Income and Living Conditions, 2011). Moreover, 8.8% of EU27 households and 17.1% of households in the 12 new Member States were in arrears on their utility bills (EU SILC, 2011). In consequences, between 50 million and 125 million people in Europe are estimated to be fuel poor (Bird *et al*., 2010; EPEE, 2011). Thus, fuel poverty is an increasingly serious problem across European Union Member States (Birol, 2007; Bouzarovski, 2012; Brunner *et al*., 2012). The notion of living conditions or relative poverty is well known, but the definition of fuel poverty is rather struggling to emerge (European Fuel Poverty and Energy Efficiency council, 2007; ONPE, 2014). Fuel poverty is not very well defined and measured in developed countries.

Fuel poverty has been regarded, and mainly treated, as a problem of monetary poverty. However, households concerned by a fuel poverty issue are not exactly the same than those concerned by monetary problems even if both phenomena are inextricably linked, representing an aspect of multidimensional poverty (Legendre and Ricci, 2014). A measure of income poverty widely adopted is the 60% of the median equalized income threshold. Palmer *et al.* (2008) estimated in 2005 in England most of the 1.5 million households in fuel poverty were also income poor. They directly link the definition of fuel poverty to monetary poverty.

Hills (2011) proposes an after fuel cost poverty approach to target low income households. This approach consists in measuring residual income after housing and fuel costs, and comparing it to the poverty treshold, often set à 60% of the median national standard of living after housing and fuel cost. The *Low Income-High Costs* (LIHC) indicator is an alternative measurement framework allowing to focus on the overlap of high costs and low income (Hills, 2011). This indicator establishes two thresholds: the same income threshold as for the "*after fuel cost poverty approach*" and an energy cost threshold, based on the median required spending of all households.

Boardman (2010) considers fuel poverty households still in a monetary perspective. A "*household is in fuel poverty if it needs to spend more than 10% of its income on fuel to maintain a satisfactory heating regime and all other energy services"*. This is the definition of energy income ratio (Department of Energy and Climate Change, 2001; De Quero and Lapostolet, 2009). Today, there are numerous criticisms of this 10% ratio approach and more generally to the exclusive cost/income approach. Measure of poverty is mainly a monetary measure using rather the gross income than the disposable income, which would be however the most relevant. Moreover, fuel poverty is not only a cost/income function; households are also affected negatively by the poor conditions of their housing such as noise or humidity (EPEE, 2006; Phimister *et al*., 2015). EPEE (2006) shows that fuel-poor households have a number of common characteristics: the incapacity to pay energy bills, cold damp living conditions, debts, homes with low energy performance and disconnection for energy supply. Consequences are numerous and sometimes, the cost/income function approach is irrelevant: low income households to cope with financial constraint adopt as primary strategy the reduction of energy expenditures. Spending on energy is usually reduced by cutting consumption (Anderson et al., 2012; Moore, 2012). Thus, the heating restriction can be a very subjective and relative notion if we do not perfectly observe it. Despite the recommendation to take into account the heating restriction to ensure the basic needs by many European organizations, the monetary definitions are largely adopted to identify fuel poor households by policy makers.

Assessing fuel poverty as a component of overall precariousness and in connection with other forms of poverty appears essential to design effective solutions. To our best knowledge, only Healy and Clinch (2002) have proposed a composite index based on subjective and objective measures to compare European countries. In their analysis, a variety of aggregate measurements of fuel poverty have been derived. Each indicator is assigned a weight, and each weight varies in the sensitivity analysis in accordance with their relevance to the qualitative definition of fuel poverty. However, this indicator remains an imperfect measure of fuel poverty, given the subjective nature of the indicators (Dubois, 2012; Thomson, 2013; ONPE, 2014; Thomson, 2014).

Thus, the original feature of this paper is to provide a fuel poverty index taking into account the three dimensions of fuel poverty: (i) monetary problems but also (ii) energy efficiency of the building and (iii) the heating restriction. These three dimensions are calculated using objective measures (the disposable income available[3] , the energy consumption and the heating restriction) and not subjective indicators.

We propose an objective measure of heating restriction: the indoor temperature. The World Health Organization presents the existing evidence of the health impacts of low temperatures in the home setting (Ormandy and Ezratty, 2012; Lacroix, 2015). Several indicators of residential thermal standards are found to be significantly related to variations in relative excess winter mortality at the 5% level (Healy, 2003). Persons experiencing fuel poverty cannot heat their homes to temperatures established as acceptable by the World Health Organisation (WHO): the main living area must have a temperature of 21 °C (WHO, 1987). Using a matching estimation, we show that households declaring being constrained live in average in less heated housing, or at least in slightly cooler housing. This result confirms first that denying the restriction in the measure of the fuel poverty leads to an underestimation of the phenomena, and secondly that temperature, compared to the WHO's standard is good proxy of heating restriction.

Finally, the purpose of this paper is not to determine which households are fuel poor. However the fuel poverty index (FPI) provides a robust scale of energy precariousness, and consequently a finest way to capture different degrees of fuel vulnerability. In consequence, it will contribute in the future to the improvement of public policies and constitutes unquestionably a value added to the literature.

The remainder of the paper is as follows. In section 1, the fuel poverty index is presented. We introduce data and variables used to calculate the fuel poverty index in section 2. Then, in order to demonstrate the relevance of the indoor temperature as a measure of heating restriction, a matching estimation is proposed in section 3. We apply the fuel poverty indicator to french data and test its robustness in the 4th section. Section 5 concludes.

[3] The French database (*PHEBUS*) in one of the first database which provides information on the disposable income. Most studies on fuel poverty uses in their analysis the private income which is less precise.

2 Construction of the Fuel Poverty Index (FPI)

The advantages to propose a composite indicator which compares fuel poverty level across households are increasingly recognized as a useful tool in policy analysis (ONPE, 2014). Such an indicator is an useful tool in identifying trends and drawing attention to particular issues. The composite indicator should ideally measure multidimensional concepts which cannot be captured by a single indicator such as energy income ratio. Composite indicator is easier to interpret than a battery of many separate indicators. The strengths of a fuel poverty composite indicator largely derive from the quality of the underlying variables (European Commission, 2008). Three indicators from the EU SILC dataset have been widely used to measure aspects of EU fuel poverty, namely, inability to keep adequately warm, living in a damp home, being in arrears on utility bills (Devalière et al., 2011; ; EPEE, 2011; Waddams Price *et al.*, 20.12; ONPE, 2014). Those variables correspond to the fuel poverty dimension identified: monetary constraint, energy inefficiency, and heating restriction. Unfortunately, only the "low income/high costs" and the energy income ratio are often used in fuel poverty analysis. Thus, we propose a composite indicator which can take into account the three indicators proposed from the EU SILC but in a normative way. Instead of just analyzing the answers to those questions, such as in the SILC survey, we propose a numeric index, the fuel poverty index (FPI), capturing these three aspects of fuel poverty. This index is based on the geometric means and it takes into account differences in achievement across dimensions. Moreover, weights can have a significant effect on the overall composite indicator. Most composite indicators rely on equal weighting (EW). This essentially implies that all variables are "worth" the same in the composite, but it could also disguise the absence of a statistical or an empirical basis, *e.g.* when there is insufficient knowledge of causal relationships or a lack of consensus on the alternative. Thus, we consider that the weights are equal.

The composite fuel poverty index (FPI) is given by:

$$FPI(P, C, R) = \sqrt[3]{I_p \times I_c \times I_R} \qquad [1]$$

With I_p is an indicator of standard of living, I_c an indicator of the housing energy inefficiency, and I_R captures the potentially heating constraint by providing information about the housing temperature. I_P, I_c, I_R allow comparing the household attributes to objective references in the three dimensions.

Equation [1] allows considering the complementarity between three dimensions across a geometric aggregation: the elasticity of the FPI to each dimension cannot be separated from the two others. Indeed, an undesirable feature of additive aggregations is the implied full compensability, such that poor performance in some indicators can be compensated for by sufficiently high values in other indicators The geometric mean reduces the level of substitutability between dimensions and at the same time ensure that a 1% decline in index of heating restriction has the same impact on the FPI as a 1% decline in income index. Thus, as a basis for comparisons of achievement, this method is also more respectful of the intrinsic differences across the dimensions than a simple average. If multi-criteria analysis entails full on-compensability, the use of a geometric aggregation is a solution (European Commission, 2008). Moreover, normalisation is required prior to any data aggregation as the indicators in a data set often have different measurement units. A number of normalisation methods exist (Freudenberg, 2003; Jacobs *et al.*, 2004). In this study, we retain a Min-Max normalizes indicators to have an identical range [0, 1] by subtracting the minimum value and dividing by the range of the indicator values. However, extreme values/or outliers could distort the transformed indicator. On the other hand, Min-Max normalisation could widen the range of indicators lying within a small interval, increasing the effect on the composite. The normalisation method should take into account the data properties, as well as the objectives of the composite indicator. Robustness tests might be needed to assess their impact on the outcomes.

First the monetary poverty is captured through I_p:

$$I_p = \frac{P - Min(P)}{\mathrm{Max}(P) - Min(P)} \qquad [2]$$

Where P is the ratio between the poverty threshold, set at 60% of the median per consumption units (PCU) disposable income, and the household PCU disposable income.

The energy per square meter consumption (C) is used to calculate I_c:

$$I_C = \frac{C - Min(C)}{\mathrm{Max}(C) - Min(C)} \quad [3]$$

Finally, the world health organization (WHO) (1987) recommends an indoor temperature of 21 degrees Celsius in living areas and has demonstrated the consequence of an inadequate temperature on health. One solution to measure the restriction is to compare effective indoor temperature to those recommended. The calculation of the last indicator is based on this recommendation:

$$I_R = \frac{R - Min(R)}{Max(R) - \mathrm{min}\,(R))} \quad [4]$$

With $R = \frac{21}{housing\ mean\ temperature}$.

One understands well that a poor housing energy performance has not the same consequences for a low income households or a rich one. If the efficiency of the accommodation deteriorates, the latter will have the means to undertake renovations. The advantage of the FPI index is to provide a scale rather than defining only households as fuel poor or not. It is up to the policy maker deciding which population of which ranges of FPI index has to be targeted with specific policies.

The FPI index will also be applicable to other countries, and depending on the extent of its use, an international scale of fuel poverty might emerge to compare worldwide the phenomena. However, to achieve comparing countries, homogenization measures of surveys are necessary. For the moment its micro-foundation let us categorize the population and estimate the intensity of the phenomena for each household.

Finally, several judgements have to be made when constructing composite indicators on the selection of indicators, data normalisation, weights and aggregation methods, etc. The robustness of the FPI may thus be contested. A combination of uncertainty and sensitivity analysis can help gauge the robustness of the indicator. Thus, sensitivity analysis to certify of the robustness of FPI is provided in section 4.2.

3. Data

The fuel poverty index is applicated using French Data based on the *PHEBUS* (Housing Performance survey, Equipment, needs and uses of energy) database. The Housing Performance survey, Equipment, needs and uses of energy is a new time survey[4]. This new punctual survey consists of two parts made separately, a face to face with the occupants of the home about their energy consumption expenditures and their energy consumption attitude, and an energy performance diagnosis of the housing[5]. The survey aims to provide information about the energy performance of the housing stock, allowing for analysis according to the households' characteristics, households' appliances, as well as their energy use and their energy consumption. In this study, attitude towards energy consumption is available. This survey is very interesting because there is very detailed information on energy consumption by type of fuel, energy costs, and energy tariffs. Information is also available on the renovations undertaken by households, incentives to renovate (achieve energy savings or improved comfort), as well as public policies. Moreover, a large part of the survey is devoted to the behavior of households and their satisfaction with their heating system. We are able to know if households restrict their energy use and what their preferences are. We know if households prefer to achieve energy savings and comfort in their homes, and this according to end-uses, that is to say, by making a distinction in consumption for hot water, electricity and heating. A part of the survey is also dedicated to indoor temperature in winter and in summer. Detailed questions are asked about the rate of occupancy. We also know if households restrict their consumption by reducing the temperature or by refusing to heat some rooms. Finally, we know if households have a feeling of discomfort

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4 The Operation Manager of the survey are: Ministry of Ecology, Sustainable Development and Energy (MEDDE); General Commission for Sustainable Development (CGDD); Service Observation and Statistics (SOeS); Under direction of the housing and construction statistics; Under the direction of energy statistics

5 The energy performance diagnosis is a document that provides an estimate of energy consumption and greenhouse gas emissions of a dwelling. It is part of the technical diagnostics record, as well as asbestos diagnostics, termites, lead and status of indoor facilities for electricity and gas. This diagnosis has been mandatory since 1 November 2006 in case of sale of a dwelling and since 1 July 2007 for leasing. The display of the energy performance of real estate in the real estate agencies has been mandatory since 1 January 2011. The diagnosis is provided free to the respondent at the end of the investigation and has a 10-year validity period.

and what the source of this feeling. Considering all these factors, we can therefore conduct a thorough analysis of the energy consumption of households, taking into account not only objective variables on the characteristics of buildings and their sociodemographic characteristics, but by considering the preferences of households. More subjective questions on satisfaction in terms of heating are also available. This study also allows studying fuel poverty with information on the disposable income, which is completely new, but also, with information about energy expenditures and attitude towards energy consumption. To our knowledge, it is rare to have a so interesting and detailed database. The survey was conducted from April to October 2013. Our sample contains 2,384 households and is representative of the population (the sample is weighted to ensure the representativeness).

4. The three dimensions of fuel poverty

In a first step, using this new database, we provide some descriptive statistics about the three dimensions of fuel poverty.

4.1 The monetary dimension

To measure the fuel poverty in monetary terms (Table 1), we examine the multiple aspects of fuel poverty in France using three different existing measurement approaches: the "*10% ratio approach (energy income ratio)"*, the *"LIHC approach"* (Low Income-High Costs indicator, also proposed by ONPE, 2014) and "*the after fuel cost poverty approach*". Under this last approach, households whose equivalised income after housing costs and domestic fuel costs is below the threshold of 60% of the equivalised national median income net of housing and domestic fuel costs are classified as fuel poor[6]. All this indicators are calculated using the disposable income, which is a value added in this paper.

[6] Definition of fuel vulnerability are also proposed by Legendre and Ricci (2015). Households are fuel vulnerable in the sense that they are *a priori* non-poor (not below the 60% of the median adjusted income) when considering income net of housing costs, but turn poor when considering income net of housing costs and domestic fuel expenses.

Table 1 Main descriptive statistics

Variables	Means (with weight) in Euros
Disposable Income	38094
Disposable Income by u.c	23807
Annual housing costs for tenants or free occupants	4657
Housing costs for homeowners or first-time buyers	3280
Total housing costs	3665
Household disposable Income - housing costs	34429
Household disposable Income - housing costs in u.c	21525
Effective energy expenditures for electricity	772
Effective energy expenditures for gas	978
Effective energy expenditures for oil	1623
Effective energy expenditures for coal	974
Total Effective energy expenditures	1465
Total Effective energy expenditures by u.c	957
Disposable income – housing costs and energy expenditures by u.c	32963
60% poverty threshold of the median (using the Disposable income – housing costs and energy expenditures by u.c)	16499

The energy income ratio is equal to 0.0482. The same ratio calculated between energy expenditures and disposable income after housing costs and domestic fuel costs increases to 0.0555. The three definitions of fuel poverty identify quite different fuel poverty rates in France: 8.48% of the population are fuel poor according to the 10% ratio approach, 7.27% according to the *LIHC approach* and 21.46% according to the *after fuel costs approach*. According to these different results and their magnitude, it seems quite complicated to determine which households are in a fuel poor situation if we refer only to monetary criterions. Moreover, as we show previously, fuel poverty is not only a cost/income function; households are also affected negatively by the poor conditions of their housing in terms of energy efficiency. Finally, despite the recommendation the take into account the energy restriction to ensure the basic needs of households, definition above remain monetary definition.

4.2 The energy efficiency of the building

To take into account the energy efficiency of the buildings, an objective measure seems to be the effective energy consumption. Even if the theoretical energy consumption would be better to measure the basic needs and to avoid error measure due to rebound effect[7], this measure is imperfect. Indeed, we have not to neglect the quality of diagnoses made by professionals who produce the energy performance of the building. Information is not completely available and assumptions must be done about the quality of wall insulation for example. Moreover, there is no control on professionals who prescribe and install equipment. Professionals have not necessary the skills to perform the diagnosis. Finally, theoretical energy consumption does not consider the number of persons as well as the number of appliances in the dwelling. As we could expect, preliminary results show a problem in the measure of the theoretical energy consumption. Even if this measure would be very interesting, the error of measure can false the results. Thus, we used the effective energy consumption. Numerous studies have already showed that energy consumption depends on energy efficiency of the building. Indeed, types of fuel used, energy prices, technical building properties, climates, and energy quality appliances determine the energy consumption (see for instance Parti and Parti, 1980 ; Dubin and McFadden, 1984; Baker et al., 1989; Nesbakken, 1999; Labandeira et al., 2006; Hossein, 2014; Wahlström and Hårsman, 2015). Main descriptive statistics are presented in the Table 2.

[7] The rebound effect appears if investment in an energy-saving technology (like double-glazing) entails a change in Household behavior (increase of temperature target for instance) which offsets the beneficial effects of the technology on energy consumption (Khazzoom, 1980).

Table 2 descriptive statistics about the effective energy consumption

	Effective Energy Consumption (in kWh/m²/year)
Individual housing units	178.5
Collective building	117.9
Dwelling constructed before 1919	147.23
Dwelling constructed between 1919 and 1945	187.6
Dwelling constructed between 1946 and 1970	180.9
Dwelling constructed between 1971 and 1990	157.1
Dwelling constructed between 1991 and 2005	145.5
Dwelling constructed after 2005	135.6
Dwelling located in climate zone H1 (coldest zone)	167.4
Dwelling located in climate zone H2 (middle zone)	154.5
Dwelling located in climate zone H3 (Mediterranean zone)	116.6
Possibility to change the indoor temperature in the dwelling	139.7
Impossibility to change the indoor temperature in the dwelling	162.9
Boiler system installed before 1986	218.5
Boiler system installed between 1987 and 1991	217.6
Boiler system installed between 1992and 1996	211.6
Boiler system installed between 1997 and 2001	184.7
Boiler system installed between 2002 and 2006	207.6
Boiler system installed between 2007 and 2012	182.9
Dwelling with a cooling system	134.7
Dwelling without a cooling system	160.6
In dwelling fuel poor occupied (energy income ratio)	260.85
In dwelling fuel poor occupied (After fuel costs approach-Hills)	242.8
Means	185.5

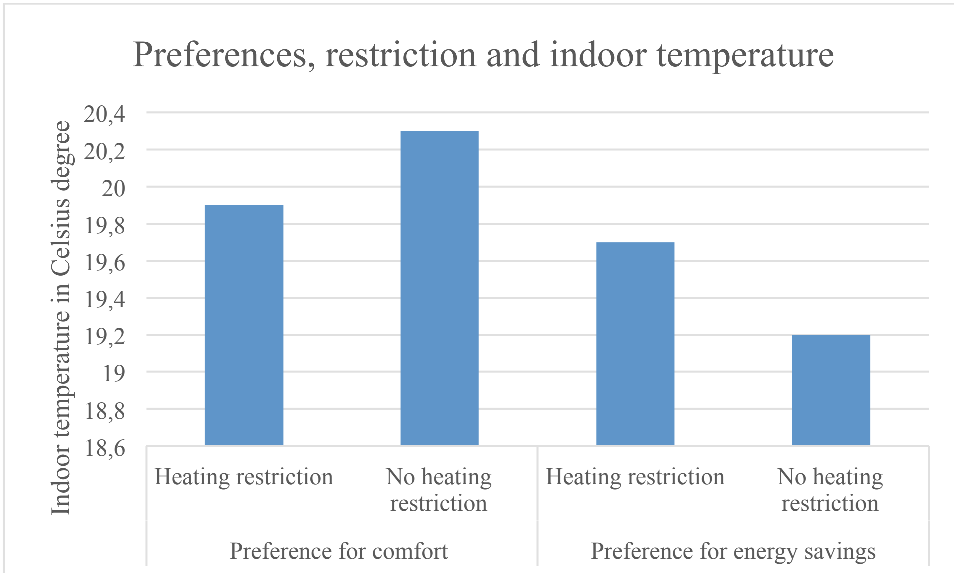
The effective energy consumption is 158.5 kWh/m² in average. Colder the climate zone (climate zone H1), higher the energy consumption. The energy consumption is also higher when the dwelling is occupied by monetary fuel poors, which can underline the bad energy efficiency of the buildings. An interesting result is obtained for period of construction. The effective energy consumption stays quite higher when the dwelling was built in the recent years. Two explanations are possible: (i) households living in recent building consume more for appliances, heating and cooling; (ii) households living in old home restrict their energy consumption. Thus, taking into account the heating restriction and the thermal discomfort is very important.

4.3 The heating restriction

The notion of heating restriction and thermal discomfort is quite complicated. Research on fuel poverty based its discussion on “adequate home heating” and “adequate warmth” (Lewis, 1982 and Boardman, 1986). This indicator is important in estimating levels of fuel poverty. It is, therefore, according to Lewis (1982) and Healy (2002) the key indicator of fuel poverty. In the database, 23 % of households declare to restrict their energy consumption. In total, 88% of households restrict their consumption by limiting or stopping their heating system. The primary ways to restrict the consumption is not to heat some rooms in the dwellings (33.73%) and the second main ways is to stop or to limit the heating system (22.1%). The other reasons are to limit the number of heating days or to choose to heat only some rooms. Households living in the old building (constructed before 1945) declare to restrict their consumption (which is in line with the previous result on effective energy consumption). In the survey, hhouseholds were asked about their behavior regarding energy consumption including voluntary restriction. However, this notion of “adequate home heating” and “adequate warmth” through declarative restriction is subjective. One way to overcome this problem would be to use an objective measure of heating restriction: the indoor temperature.

We note that households who declare to restrict their consumption have also a lower indoor temperature compared to other households (19.3°C against 19.9 in average). Moreover, households who declared a cold discomfort during the winter in the accommodation have an average indoor temperature of 19.5°C. To ensure that the indoor temperature can be a good proxy for the heating restriction, we proceed to a matching estimation. We can compare indoor temperature between households who declared to restrain their energy consumption to the others with same characteristics. In the database, 56% of households declare to prefer comfort for heating instead of energy savings. Their indoor temperature is 20,7°C (against 19.3 respectively). Generally, temperature is lower in dwelling where households have preferences for energy savings (Figure 1).

Figure 1: Preferences, restriction and indoor temperature



i. Measure of heating restriction: the econometric estimation

- Methodology

Proxy measures can be used when the desired data are unavailable or comparability is limited. Thus, in order to measure the impact of the heating restriction, it is necessary to evaluate the difference in an outcome variable. We select the mean housing temperature in order to verify if the restriction leads to objective differences with households who do not declare restricting their heating energy consumption.

Households, potentially constrained, are denoted i. A vector x of control variables represents their personal attributes and their housing characteristics. The binary variable (the treatment variable), denoted R, reports whether the household declares restraining its heating energy consumption, or not. For the treated sample, we have $R = 1$, and for the control group, $R = 0$.

Only a perfectly randomized evaluation allows avoiding a selection bias in the estimation. In that case, comparing the outcome variable difference between treated and untreated individuals provides the impact of the treatment (Rubin, 1974). However, in most cases, the independence between the probability of being treated and the personal attributes can absolutely not being assumed. In our case, restraining the heating energy consumption is undoubtedly strongly linked with household's characteristics, including its housing conditions. The present study is based on non-experimental data. So we use a non-experimental method to estimate the impact of the heating consumption constraint. The impact should ideally be the difference between the outcome variable (Y) for the constrained households (Y_1) and this variable if the household would not have been constrained (Y_0):

$$\beta(x) = E[Y_1 / R = 1, X = x] - E[Y_0 / R = 1, X = x] \qquad [1]$$

With:

$$Y = RY_1 + (1 - R)Y_0 \qquad [2]$$

Y_1 and Y_1 cannot be observed simultaneously. In consequence, the counterfactual temperature has to be calculated. We use matching estimators which requires matching each constrained household with one or many unconstrained households. Rubin (1974) proposed to match observations on observable characteristics. We have to find, from a large sample of unconstrained households, households who are similar to the constrained ones in terms of characteristics not affected by the heating energy consumption restriction (the treatment). Under the assumption that heating energy constraint is solely based on differences in observable attributes, the corresponding constraint effect can be measured even if it is not random. Each constrained household is matched to an unconstrained household on the basis of the probability of being constrained, conditionally on the different observed characteristics x. This conditional probability is the propensity score (Rosenbaum and Rubin, 1983). Rosenbaum and Rubin (1983) show that matching on $R(x)$ is as good as matching on x. Key assumptions for identification of the constraint effect are conditional independence –or *unconfoundedness* (Rosenbaum and Rubin, 1983)- and the presence of a propensity score density common support (Heckman, LaLonde, and Smith, 1999). Under those assumptions, the propensity score matching average treatment is then equal to the mean difference in temperature over the common support.

We perform first one of the most frequently used matching techniques, the nearest neighbor (NN) matching and match, as usually done, the treated observations with the 5 closest controls. This estimator implies a comparison between each treated units and the closest untreated observation, in terms of propensity score.

However, one drawback of the NN method is that only a small sample of unconstrained households can ultimately satisfy the criteria to constitute the common support and allow constructing the contrefactual outcome. For this reason, nonparametric matching estimators such as kernel matching are used to construct a counterfactual match for each treated unit by using weighted average of all untreated units. The weights ($\omega(.)$) for kernel matching are given by:

$$\omega(i,j) = \frac{K\left(\frac{P_j - P_i}{a_n}\right)}{\sum_{k \in C}\left(\frac{P_k - P_i}{a_n}\right)} \qquad [3]$$

Where P_i is the propensity score for a constrained household and P_j, the propensity score for an untreated household, included in the control sample (C). K(.) is a kernel function and a_n a bandwidth parameter. Robust standard errors are calculated using boostrap as the estimators are asymptotically linear (Imbens, 2004). Boostrapping standard errors allows also taking into account the variance due to the derivation of the propensity score matching and the determination of the common support (Heckman, Ichimura, and Todd, 1998; Efron and Tibshirani 1993; Horowitz, 2003). The variables used for analysis are presented in section A in appendix.

- Results

We present the results of our two step analysis. First of all, we calculate the propensity scores (the probability of being constrained). The details of this step are available in appendix B. Then, the second step consists in the calculation of temperature differentials using nearest neighbor and kernel matching methods.

Table 3 Mean average treatment effect

	Average restriction effect	**Robust standard errors**
Nearest neighor (5) matching	-0,4823938	0,1016755***
Kernal matching	-0,4704556	0,0912952***

Notes: *** Significant at 1%, ** significant at 5%, * significant at 10%

Households declaring being constrained live in average in less heated housing, or at least in slightly cooler housing. In average, the temperature in their accommodation is 0.5 to 0.6 degrees lower[8] (Table 3). This result confirms that denying the restriction in the calculation of the fuel poverty leads to an underestimation of the phenomena. Considering the average restriction impact on the temperature, a relevant fuel poverty measure should include not only monetary constraints, but also objective housing characteristics such as energy consumption and temperature. This could be a way to integrate simultaneously a monetary aspect, an energy efficiency aspect, but also taking into account the wellbeing through the mean temperature. The heating restriction impact could be captured in a normative way. For this reason, we consider it is necessary to propose a numeric index (FPI) capturing these three aspects of fuel poverty. In the next part, we provide some empirical comparison of the FPI to other measures of fuel poverty. We also check the robustness of the FPI.

5. Values of the FPI and its components in the French case

5.1 FPI and comparisons with other measures of fuel poverty

75% of the population has a value of FPI lower than 0.119 and 99% has a value lower than 0.198. Table 4 summarizes the different components of the composite fuel poverty index which reaches in the French case 0.164. We note that both fuel poverty definitions of the *10%* and the *LIHC* encompasse very similar profiles of households. *Ic* reaches indeed for Poors according to the *10%* definition about 0,0776, which is 65% (0,0776/0,0469) higher than for non Poors. For fuel Poors according to the *LIHC approach*, *Ic* is only 52% higher than for non Poor. By contrast, *Ic* for the Poors according to the *after fuel costs approach*, the energy consumption indicator represents only 97% of the indicator for non Poors. Statisctics presented in table 5 allow to confirm that the *after fuel costs approach* definition is very close to a definition of monetary poverty. The indicator of financial hardships I_P is indeed 86% higher for Poors than for non

[8] This result is confirmed when performing radius matching and stratification matching methods.

Poors, whereas the difference between Poors and non Poors is only 62% according to the *LIHC* definition.

Table 4 FPI index and its 3 dimensions indicators

	(weighted) Mean	Min	Max
P	0.69	0.05	3.97
C	158.52	0.00	3126.94
R	1.06	0.75	2.63
Ip	0.16	0.00	1.00
Ic	0.05	0.00	1.00
Ir	0.16	0.00	1.00
FPI	0.10	0.00	0.36

Figure 2: Kernel density estimate of FPI

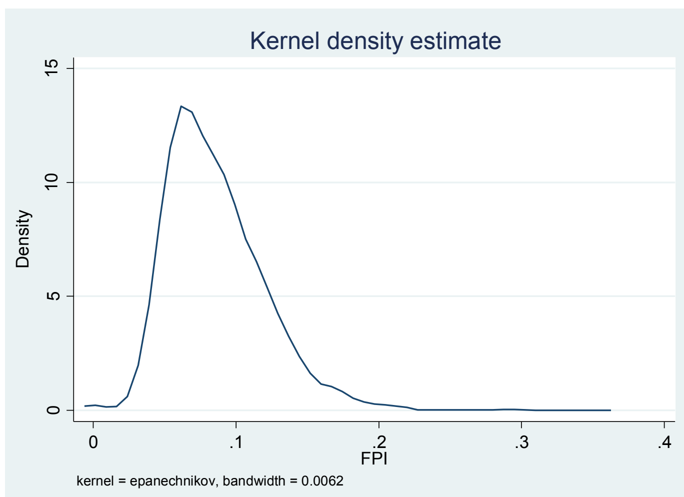


Figure 2 shows the repartition of the population according to the value of the FPI.

Compared with other fuel poverty measure, the *10% definition* seems to better include simultaneously those who cumulate relative financial hardships and relative high energy consumption/m2 (Table 5). I_P and I_C are higher for them than for the fuel poor according to the two other definitions. The relative heating restriction is the highest for the poor according to the a*fter fuel costs approach* definition.

Table 5 FPI and other fuel poverty measures

	Fuel poor according to the definition of…			Not fuel poor…		
	10%	**LIHC**	**After fuel costs approach**	**10%**	**LIHC**	**After fuel costs approach**
I_P	0.2652	0.2525	0.2561	0.1485	0.1558	0.1374
I_C	0.0776	0.0741	0.0497	0.0469	0.0488	0.0509
I_R	0.1677	0.1705	0.1716	0.1638	0.1638	0.1623
FPI	0.1401	0.1399	0.1180	0.0954	0.0978	0.0962

To demonstrate that the FPI is an adequate measure of fuel poverty, we compare the three dimensions that a relevant defintion should take into account (EPEE, 2006; ONPE, 2014) with the other measures of fuel poverty (see Table 6). The value of the FPI is quite stable among the different measures of fuel poverty.

Looking more precisely at the FPI and other monetary defintions of fuel poverty, the most interesting result concerns the disposable income. Results show that the FPI really does not only take into account the monetary constraint but also other dimensions. There are indeeed nonlinear effects of income. Households can have a high FPI (being in the 10th decile) and having a standard of living quite higher than Fuel Poors'standard of living (in average 12626 euros for all households in the 10th decile of FPI, and less than 11800 euros for Fuel Poors according to the three definition of fuel poverty in the 10th decile of FPI also) (Table 6). Altough their standard of living appears quite higher, their high energy consumption (323 kWh per m2, and less than 305 for the fuel Poor) and their restriction increases their FPI value and compensate partly the relative better monetary indicator.

The similitude of both *10%* and *LIHC definitions* is confirmed in the table 6: profiles of Poors according both definitions appear quite close along the 10 deciles of FPI. Standard of living for

Fuel Poors according to those definitions reaches about 11800 euros in the 10th decile, their indoor temperature is about 19.34°C, and their annual energy consumption levels are respectively 303 and 304 kWh per m2. Conversely, the profile of Fuel Poors according to the *after fuel cost defintion* is very different, as those figures are respectively equal to 10601 euros, 19.1°C and 266.32 kWh for them.

Eventually, almost 80% of the Fuel Poors according to the *10%* and *LIHC definitions* belongs to the 3 highest decile of FPI, there are only 52% of the fuel Poors according to the *after fuel costs approach*.

Table 6 Comparisons of the indicators and the other fuel poverty measures

Percentile of FPI	FPI	Mean PCU disposable income	Mean Temperature (°C)	Mean energy consumption /m2 (kWh)	% of fuel poors
		Poors according to the *10% definition*			
1	0.054	23003	19.7	23.5	3%
2	0.069	15008	19.0	26.6	0%
3	0.083	18614	20.0	95.2	1%
4	-	-	-	-	0%
5	0.094	16549	22.5	188.7	3%
6	0.102	13280	20.5	98.1	5%
7	0.109	16551	20.9	169.1	6%
8	0.118	17480	20.1	193.0	14%
9	0.135	15230	20.2	240.5	18%
10	0.166*	11796	19.3	303.3	49%**
		Poors according to the *LIHC*			
1	0.048	15012	20.5	15.4	1%
2	0.070	17864	19.7	38.6	0%
3	0.080	17015	20.5	68.8	0%
4	0.088	16966	20.9	88.5	1%
5	0.095	15806	20.3	99.7	3%
6	0.102	14800	20.1	104.7	6%
7	0.109	16022	20.0	135.9	7%
8	0.118	15214	19.8	158.2	17%
9	0.132	12737	19.7	184.6	17%
10	0.166	10601	19.0	266.3	47%
		Poors according to the *After fuel costs approach*			
1	0.050	19484	20.0	15.9	7%
2	0.069	15008	19.0	26.6	5%
3	0.082	16960	26.0	308.6	3%
4	0.086	22161	22.0	135.1	6%
5	0.094	15674	21.7	139.4	7%

6	0.102	15517	19.9	107.6	10%
7	0.110	15094	20.1	129.4	9%
8	0.117	17157	19.8	172.7	13%
9	0.132	14832	20.0	222.4	11%
10	0.168	11760	19.3	304.3	28%
		FPI of the total sample			
1	0.05	36569	20.7	42.3	
2	0.0689	29310	20.4	76.7	
3	0.080	29906	20.2	111.5	
4	0.088	26930	20.1	126.3	
5	0.0945	24429	20.2	152.2	
6	0.102	21685	19.9	149.7	
7	0.110	20396	19.9	173.7	
8	0.119	18699	19.7	196.7	
9	0.131	16950	19.6	232.9	
10	0.165	12626	19.0	323.6	

Note : According to the *10% ratio* definition, the 10% with the highest FPI have an average index of 0.166.
**Moreover, 49% of fuel Poors belong to the highest decile of FPI.

The FPI has the huge advantage to include all the dimensions of fuel poverty which was not the case for fuel poverty definitions until today. It provides a scale of fuel vulnerability rather than only a binary indicator. It is now the role for policy makers to adapt the energy surveys so that FPI will allow providing some comparisons over time and countries.

5.2 Sensitivity analysis

Several judgements have to be made when constructing composite indicators, *e.g.* on the selection of indicators, data normalisation, weights and aggregation methods, etc. The robustness of the composite indicators and the underlying policy messages may thus be contested. In the case of fuel poverty index, the selection of indicators is fairly consensual (ONPE, 2014) as well as the choice of a geometric means in order to avoid error measurement (due to exclusion of one dimension).

Thus, in this study, some robustness and sensitivity analyses can be undertaken to assess the robustness of the fuel composite indicator in terms of, e.g., the mechanism for calculating single indicators, the normalisation scheme and the withdrawal of extreme value data. Indeed, we can refine both the sensitivity analysis and the standardisation of basic indicators by thinking about the minimum and maximum values set for the poverty and the restriction dimension. Thus, the sensitivity of the composite indicator can be tested by defining minimum and maximum values for the reference values and can be compared with the results obtained previously. If the values are quite similar, the composite indicator shows the importance to take into account three dimensions with a similar weight. This can avoid error measurement of fuel poverty due to changes in indicator for instance.

We propose different sensitivity analysis to assess whether our composite indicator is robust in their 3 dimensions. We conduct sensitivity analyses to extreme values (Table 7). Observations for the population who have the 5% lowest value and the 5% highest value for each dimension separately are removed. Results of the FPI are also compared with sensitivity to the poverty threshold and the reference temperature set by WHO (Table 8).

Table 7 Sensitivity analysis to extreme values

Percentile of FPI	Without extreme value* for PCU disposable income	Without extreme value* for temperature	Without extreme value* for consumption	Without extreme value* for FPI
1	0.0507	0.0515	0.0540	0.0586
2	0.0698	0.0698	0.0699	0.0698
3	0.0801	0.0801	0.0801	0.0801
4	0.0881	0.0881	0.0881	0.0881
5	0.0949	0.0949	0.0950	0.0949
6	0.1021	0.1021	0.1021	0.1021
7	0.1098	0.1097	0.1097	0.1097
8	0.1189	0.1190	0.1189	0.1189
9	0.1310	0.1310	0.1310	0.1310
10	0.1602	0.1622	0.1601	0.1476
Means	0.0984	0.1007	0.1012	0.0995

Note : by removing the 5% of the population whose values are the lowest and 5% of the population whose values are the highest

Table 8: sensitivity analysis to reference values

	Reference	With a poverty threshold of 50%	20°C temperature
P	0.69	0.57	-
P min	0.05	0.04	-
P max	3.97	3.31	-
R	1.06	-	1.01
R min	0.75	-	0.71
R max	2.63	-	2.50
Ip	0.16	0.16	0.16
Ic	0.05	0.05	0.05
Ir	0.16	0.16	0.16
FPI	0.10	0.10	0.10

Results show us that the fuel poverty composite indicator continues to be around 0.10 despite we decrease the reference values from 60% of the median PCU to 50% for the poverty threshold and from 21 to 20°C for temperature. Even if the minimum and maximum values change in one indicator, results on overall are not affected. The FPI is also robust to outliers. In consequence, we illustrate how our methodology is robust and useful for fuel poverty households' classification.

6. Conclusion

Fuel poverty is an increasingly serious problem across countries. However, fuel poverty is not very well defined and measured. Today, fuel poverty measure which takes into account monetary constraint, bad energy efficiency of the dwelling and heating restriction does not exist. Indeed, we know rather well the notion of living conditions or relative poverty, but the definition of fuel poverty is rather struggling to emerge. Three indicators from the EU SILC dataset have been widely used to measure aspects of EU fuel poverty, namely, inability to keep adequately warm, living in a damp home, being in arrears on utility bills. However, such proxy indicators are an imperfect measure of fuel poverty, given the subjective nature of the indicators, the potential for error of exclusion whereby respondents do not identify as fuel. Thus, the major original feature of this paper is to provide the first fuel poverty index taking into account the three dimensions of fuel poverty. This index is applied with new French data, the *PHEBUS* database. The three dimensions are calculated using objective measures rather than subjective indicators. These objectives measures are (i) the disposable income, (ii) the energy consumption and (iii) the indoor temperature. Using a matching estimation, the quality of the indoor temperature as a proxy of heating restriction is demonstrated. The purpose of this paper is not to determine which households are fuel poor and in consequence to provide policy recommendations: poverty thresholds should be determined by policy makers. But, the fuel poverty index can contribute in the future to the improvement of public policies and constitutes unquestionably a added value to the literature. Today, many households are excluded from the definition and are not well targeted by policy makers. Moreover, in the future, this index could be useful to make some comparisons between households inside a country, but also, once aggregated, some international comparisons. However, the quality and accuracy of the fuel poverty composite indicator should evolve in parallel with improvements in data collection and indicator development. Government should provide further impetus to improving data collections, identifying new data sources and enhancing the international comparability of statistics. It is now the role for policy makers to adapt the energy surveys in order to calculate the FPI to let some comparisons over time and countries.

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Appendix

A. Variables used in the matching estimation

We balance both subsamples (treated and untreated) by using dummy variables of income percentiles, homeownership, and size of the living urban area. We include also a binary variable capturing whether the household has the possibility to adjust the heating energy consumption, because in some collective housing, it is not possible. The housing characteristics are introduced with the construction period, and the energy consumption classification, indicating if the housing is efficient. Energy label classification provides insight into the energy efficiency of the dwelling. The energy label for dwellings goes from A to G. The A label is the most energy-efficient, while the G label is the least efficient. Considering energy consumption is available in the database, it is possible to split to determine energy label for each dwelling.

Finally, households preferences are included via the answer to the question “do you prefer reaching your comfort temperature or saving the heating cost?”.

Urban areas include: rural areas (urban area size 0), areas with 2000 to 9999 inhabitants (urban area size 1), areas with 10000 to 99999 inhabitants (urban area size 2), areas with 100000 to 1999999 inhabitants (urban area size 3), and Paris (urban area size 4).

The construction periods allows controlling thermal performances, as current thermal regulation was implemented in the 70’s. Finally, we have to secure that the restriction feeling declared by the treated observations does not come only from a high preference for the heat, so we include the preference variable.

Control variables are summarized in the Table A-1. Column 1 gives details on constrained households who represent 23% of the sample. All controls include unconstrained households allowing respecting the balancing property. These first descriptive statistics suggest that the heating restriction is linked to the occupation status, the housing type and the preferences for heating savings cost. Housing seems also less energy efficient among treated households.

Columns 3 and 4 provide descriptive statistics for matched individuals, belonging to the control group and corresponding to the estimations reported in the section 3.3. Treated observations and matched households have very close characteristics; consequently, we can calculate the propensity score and then estimate the average treatment effect.

Table A-1 Pre treatment characteristics

Control variables	Treated	All controls	Matched controls (NN5)	Matched controls (Kernel)
Percentile 1	0.27413	0.15075	0.28649	0.26967
Percentile 2	0.20656	0.17382	0.19961	0.20303
Percentile 5	0.1332	0.25644	0.13707	0.13898
Percentile 4	0.19112	0.22103	0.18803	0.19342
Age	55.139	56.031	54.501	55.188
Homeowner	0.639	0.78004	0.65019	0.65905
Possibility to adjust the heating system	0.86293	0.80955	0.85753	0.86273
House	0.70077	0.73766	0.71622	0.71647
Urban area size 0	0.22201	0.26878	0.21815	0.23123
Urban area size 1	0.12741	0.12124	0.13359	0.13197
Urban area size 3	0.22008	0.18294	0.22934	0.21091
Urban area size 4	0.13127	0.12876	0.11351	0.11923
Preference for heating	0.23938	0.67006	0.23629	0.24623
Construction period : after 1971	0.52703	0.57082	0.53475	0.52727
DPE classification A or B	0.01351	0.02629	0.01351	0.0115

B. Estimation of the propensity scores

The probability of restraining its heating energy consumption is significantly impacted by the standard of living, homeownership, the possibility to adjust the heating system, Preference for heating savings cost and the period of construction. These results are in line with Healy (2002, 2003). Being homeowner of a recent housing and belonging to the highest percentile seems to protect against the restriction. However, having the possibility to adjust the heating system has a positive and significant impact. In average, the literature reports indeed that having a collective boiler or being linked to a district heating system prevent more from fuel poverty as defined until now.

Table B-1 Estimation of the propensity scores

	Coef.	Standard errors
Percentile 1	0.282344	0.0991691**
Percentile 2	0.068315	0.0994617
Percentile 5	-0.30103	0.1035432**
Percentile 4	-0.02056	0.0981589
Age	-0.00061	0.0021205
Homeowner	-0.24461	0.0797127**
Possibility to adjust the heating system	0.367879	0.0877896***
House	0.070968	0.0869017
Urban area size 0	-0.04439	0.0891992
Urban area size 1	0.004236	0.1059827
Urban area size 3	0.020933	0.0909609
Urban area size 4	0.107272	0.1082706
Preference for heating	-1.02455	0.0638469***
Construction period : after 1971	-0.06337	0.0633198
DPE classification A or B	-0.3535	0.2491395
Constant	-0.41904	0.1756322
Log Likelihood	-1055.2568	
No observations	2383	

Notes: *** Significant at 1%, ** significant at 5%, * significant at 10%

The estimation of the propensity scores (Table B-1) also suggests that the restriction comes from a budget constraint than a low energy efficiency of the housing. The preference variable is strongly significant and positive: the constrained households declare a preference for heating savings cost, rather than a more comfortable inside temperature. Finally, the energy classification does not seem to have any impact on the propensity scores.