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Dorothee Charlier, Bérangeère Legendre

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A Multidimensional Approach to Measuring Fuel Poverty

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Abstract

In this study we suggest that a more careful and systematic understanding of fuel poverty can be developed through a multidimensional approach to the relationship between monetary poverty, residential energy efficiency, and heating restriction. Our objective is to provide new ways to better identify those who suffer the most from fuel poverty to optimize policy. Thus, the purpose of this paper is to measure poverty in three steps following Sen (1979): (i) combining poverty characteristics into an aggregate measure involving a fuel poverty index (FPI), (ii) identification and comparison of poor people according to existing and new definitions and (iii) testing the robustness of the fuel poverty composite indicator. Our results show that the usual measures reveal a gap that does not consider all the dimensions of fuel poverty, excluding those who are at or above a certain threshold, but who are nevertheless vulnerable. The multidimensional approach enables us to consider all the components of fuel poverty.

Keywords: Fuel poverty; Multidimensional approach; Heating restriction; Thermal discomfort.

JEL codes: Q41. C43. C31. D12. R20

1. Introduction

Fuel poverty occurs when a household is unable to afford the most basic amount of energy for adequate heating, cooking, lighting, and use of appliances in the home. In 2011, 9.8% of households in the EU27 countries and 15.8% of households in the 12 new member states could not afford to heat their homes adequately ([European University Institute 2011](#)). Moreover, 8.8% of EU27 households and 17.1% of households in the 12 new member states were in arrears on their utility bills¹ ([European University Institute 2011](#)), so between 50 million and 125 million people in Europe are estimated to be fuel poor which represents respectively between 10% and 25% of European population ([Bird, Campbell, and Lawton 2010](#), [European Fuel Poverty and Energy Efficiency 2007, 2011](#)). Thus, fuel poverty is an increasingly serious problem across Europe² ([Birol 2007](#), [Bouzarovski, Petrova, and Sarlamanov 2012](#), [Brunner, Spitzer, and Christanell 2012](#)) and requires the intervention of policymakers. Indeed, [ONPE \(2016\)](#) estimates the number of fuel-poor households in France to be 3.8 million (5,8% of population).

In particular, (i) corrective measures have been implemented which aim to help fuel-poor households pay their energy bills, and (ii) preventive policies have also been introduced, which focus more on improving residential energy efficiency. Debates about the effectiveness of these measures have ensued for several reasons; mainly because energy retrofit renovations have often been undertaken by wealthier households ([Charlier, Risch, and Salmon 2018](#), [Vilches, Barrios Padura, and Molina Huelva 2017](#)). Thus, despite these measures, given the expected increase in the cost of energy, some could find it difficult or even impossible to satisfy their energy needs. The relationship between subjective well-being and the affordability for

¹ Information on the ability to keep one's home adequately warm and arrears on utility bills is from the Eurostat European Union Statistics on Income and Living Conditions (EU-SILC) Survey. The survey aims to collect timely and comparable cross-sectional and longitudinal multidimensional microdata on income, poverty, social exclusion and living conditions. This instrument is anchored in the European Statistical System (ESS). The inability to keep one's home adequately warm refers to the percentage of persons in the total population who are in a state of enforced inability to keep their home adequately warm. Arrears on utility bills refers to the percentage of persons in the total population who are in a state of arrears on utility bills, expressing the enforced inability to pay their utility bills on time due to financial difficulties.

² Fuel poverty is a major social problem which requires action across a range of policy issues and at all political levels. The number of fuel-poor households in Europe could multiply in the near future, as nearly one in seven households in Europe are at risk of poverty, the price of domestic gas increased by 18% on average from 2005 to 2007, and the price of domestic electricity increased by 14% on average over the same period..([European Fuel Poverty and Energy Efficiency 2011](#))

households of electricity, heating oil and natural gas has been already demonstrated (Welsh and Bierman 2017).

As a prerequisite to discussions about the effectiveness of different measures to fight fuel poverty, debates have often focused on the need to reliably identify fuel-poor households and create a detailed profile of such households. In fact, the multidimensionality of fuel poverty makes it difficult to achieve this.

Fuel poverty has generally been treated as a monetary poverty problem. At European Union level, there is no common definition or standardized indicator for assessing fuel poverty. While there is a large body of literature on measuring poverty ([Ravallion 1998](#), [Phradan and Ravallion 1998](#), [Ravallion and Bedani 1994](#)) consensus has not yet been reached on the related methodological and conceptual issues. Only four countries have defined the concept of poverty and energy poverty: The United Kingdom, Ireland, France and Slovakia ([Host et al. 2014](#)). However, households affected by fuel poverty are not always the same as those affected by monetary problems, even if the two phenomena are inextricably linked, representing an aspect of multidimensional poverty ([Legendre and Ricci 2015](#)).

In this context, we suggest that a more careful and systematic understanding can be developed through a multidimensional approach to the relationship between monetary poverty, residential energy efficiency of buildings, and heating restrictions. Our objective in this paper is not to challenge existing measures of fuel poverty, but provide new ways to better identify those who suffer the most from fuel poverty in order to optimize policy. We argue this is needed to better identify the connection between energy use and well-being and therefore deepen understanding of energy poverty or energy precarity.

Current definitions of fuel poverty underscore the need to consider its multiple dimensions. Depending on the country, the definition of fuel poverty might include indoor temperature, cooling expenditures, damp walls and/or floors, lack of central heating, and rotted window frames.

Moreover, the literature has begun to highlight the need for a theoretical framework for fuel poverty similar to Sen's work on poverty ([Sen 1979](#)). Over the past 20 years, many involved in energy issues have grappled with the concept of energy poverty ([Krugmann and Goldemberg 1983](#), [Pachauri and Spreng 2003](#), [Foster, Tre, and Wodon 2000](#), [González-Eguino 2015](#)), and

several approaches have been used to define and measure it ([Department of International Development 2002](#)). These methods often define a minimum level of physical energy expenditures above which households can be considered non-poor. This level is based on a basket of goods and services for meeting direct energy needs (e.g. heating, lighting and cooking) and the energy embodied in additional goods and services that households use. However, a problem arises in assessing the minimum level of energy required for basic needs, which can be different among countries and climates. Thus, consensus on a common definition and harmonizing the use of fuel poverty indicators is still needed in developed countries. Indeed, it is difficult to identify all the dimensions of fuel poverty, notably self-imposed heating restrictions, and the usual definitions result in an amalgamation of fuel poverty characteristics ([Charlier, Risch, and Salmon 2015](#)), such that policymakers have difficulty identifying the fuel poor. Households around a certain threshold may be excluded from the definition of fuel poverty, yet still be vulnerable.

Within the same country, regional differences in climate, different socioeconomic characteristics (cost of living), and cultural factors necessarily influence the phenomenon of fuel poverty. Existing monetary indicators are not sufficient for a single, satisfactory conceptual framework that can make comparisons and capture inequalities from the local to the national to the global level to reveal more about variations between developed countries. On the other hand, assessing fuel poverty as a component of overall precarity and viewing it as connected to other forms of poverty appears essential to designing effective solutions. A convincing assessment of energy insecurity requires a broad and above all non-binary approach. The object of our research is to capture the phenomenon as a whole while retaining the elements to be considered, as well as the objectives created by binary measurement tools. We achieve this by controlling for specific regions. The results of our work will enable policymakers to adopt appropriate fuel poverty control strategies based on the distribution of the phenomenon in the population. Thus, the purpose of this paper is to measure poverty in three steps according to Sen's work (1979): (i) combining poverty characteristics into an aggregate measure involving a fuel poverty index (FPI), (ii) identification and comparison of poor people according to existing and new definitions and (iii) testing the robustness of the fuel poverty composite indicator. Our results show that the usual measures amalgamate the characteristics of fuel poverty, while the multidimensional approach enables us to consider all the components of fuel poverty: objective measures (monetary poverty, heating privation, and residential energy efficiency) as well as subjective measures such as thermal discomfort. Moreover, the fuel

poverty composite indicator continues to be around 0.107 even when the robustness of the fuel poverty composite indicator is assessed in terms of the mechanism for calculating single indicators, the normalization scheme, and the removal of extreme value data. This new index provides a robust scale of energy precarity, and consequently a more precise way of capturing different degrees of fuel vulnerability. Thus, we contribute to the literature by proposing a global and quantified approach to energy poverty in a developed country by means of a multidimensional index.

The remainder of the paper is organized as follows. In section 2.1, a review of the literature on standard measures of fuel poverty is presented. Then, in section 2.2, we introduce our multidimensional approach and fuel poverty index. In section 3, we present the data. Household profiles are examined according to the different definitions of fuel poverty in section 4.1, and we demonstrate the robustness of the multidimensional approach in sections 4.2 and 4.3. Section 5 concludes.

2. Measuring fuel poverty in France

2.1. Standard measures of fuel poverty

From a general point of view, a household is considered to be fuel poor when it occupies an energy-inefficient dwelling and is unable to pay the bills for heating the home at an appropriate level. Thus, fuel poverty refers to a multidimensional concept that includes three phenomena: the socioeconomic situation of the household according to income level, the characteristics of the dwelling including energy efficiency, and the energy access conditions generally reflected in the price of energy ([European Fuel Poverty and Energy Efficiency 2006](#), [Devalière 2007](#), [Palmer, MacInnes, and Kenway 2008](#)). One of the first measures of fuel poverty, the energy income ratio or the 10% approach, was proposed by [Boardman \(1991\)](#).

- The 10% approach

The energy-income ratio is defined as a “household [being] 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” ([De Quero and Lapostolet 2009](#), [Department of Energy and Climate Change 2001](#)). The energy-income ratio, representing this 10% indicator, is calculated as follows:

$$\text{Energy income ratio} = \frac{\text{theoretical fuel costs}}{\text{Income}}$$

[1]

One main advantage of this ratio is that it considers theoretical rather than actual fuel costs. They are obtained by multiplying fuel requirements (theoretical consumption) by fuel prices. Considering theoretical fuel costs ensures that the household achieves an adequate level of warmth subject to a range of dwelling and household characteristics. However, this measure of fuel poverty has some limits. Although the energy-income ratio has the advantage of taking into account under-consumption by comparing theoretical and effective (or real) fuel consumption, it is not in fact intended to measure whether households are spending more than 10% of their income on domestic fuel. Rather, it measures whether households would need to do so to achieve an acceptable level of warmth in their dwelling on the basis of observed income and modeled physical data related to dwelling space and thermal efficiency ([Legendre and Ricci 2015](#), [Fahmy 2011](#)). Fuel poverty is not only a cost-income function; households are also negatively affected by the poor condition of their housing in terms of noise (due to the absence of insulation) and humidity ([European Fuel Poverty and Energy Efficiency 2006](#), [Phimister, Vera-Toscano, and Roberts 2015](#)). Moreover, measuring theoretical needs and obtaining reliable physical data is complicated and controversial ([Allibe 2012](#)). Results show that the ratio between observed consumption and theoretical consumption is always less than 1, meaning that theoretical consumption exceeds observed consumption. This can be mainly attributed to restrictions in thermal comfort. Consequently, the energy-income ratio does not take into account the restriction practices of some households, mainly with regard to heating needs, induced by high fuel costs ([Dutreix et al. 2014](#)). Furthermore, [Hills \(2011\)](#) and [Moore \(2012\)](#) argue that the energy-income ratio does not reliably take income level into account, especially for high-income households. Therefore, a significant number of households are found to be fuel poor, when in reality their large fuel expenditures are in line with their high income. Although the 10% indicator is still applied in different national contexts, it is definitely not suitable for policymaking because it was defined using an obsolete and country-specific threshold of energy expenditures. It could be revisited and made more suitable using specific national characteristics. Considering these limits, the After Fuel Cost Poverty (AFCP) indicator was developed by [Hills \(2011\)](#).

— The AFCP indicator

This indicator is based on the comparison between the equivalized income of a given household and the standard threshold of 60% of equivalized national income, where income is considered after subtracting housing costs and domestic fuel costs. Under this approach, households whose equivalized income after housing costs and domestic fuel costs is below the threshold of 60% of the equivalized national median income net of housing and domestic fuel costs are classified as fuel poor³. According to this indicator, fuel poverty exists if:

$$\left\{ \begin{array}{l} \text{Equivalised (income – housing costs – Domestic fuel costs)} < \\ 60\% \text{ Equivalised (Median income – Housing costs – Domestic fuel costs)} \end{array} \right.$$

[2]

The main advantage of the AFPCP indicator is that it considers housing costs. Even if housing costs represent only a part of constrained expenditures, the results become more reliable when they are included in calculations. On the other hand, it is possible some very low-income households will be classified as fuel poor regardless of their fuel requirements. As a consequence, confusion between fuel and monetary poverty is possible ([Legendre and Ricci 2015](#)).

— The Low Income-High Cost (LIHC) indicator

Defined by [Hills \(2011, 2012\)](#), the LIHC indicator is an alternative measurement framework that focuses on the overlap of high costs and low income. This indicator considers two thresholds for identifying fuel-poor households: The first threshold is the same income threshold as for the AFPCP approach, and the second is an energy cost threshold based on the median spending of all households.

Therefore, according to this approach, a household is fuel poor in the following double condition:

$$\left\{ \begin{array}{l} \text{Equivalized disposal income} \leq 60\% \text{ (Equivalized median disposal income)} \\ \text{Equivalized fuel expenditures} \geq \text{Required national median fuel expenditures} \end{array} \right.$$

[3]

³ [Legendre and Ricci \(2015\)](#). Households are fuel vulnerable when they are *a priori* non-poor (not below the 60% of the median adjusted income) when considering income net of housing costs but are poor when considering income net of housing costs and domestic fuel expenses.

The advantage of the LIHC indicator is in clearly distinguishing between fuel and monetary poverty by defining two different thresholds. However, like the AFCP indicator, the LIHC is based on a calculation of net income and not on constrained income.

Clearly, it is necessary to agree upon social measures (i.e. the absence of a central heating system in the home, damp walls and/or floors, rotten window frames, access to an electricity grid, indoor temperature) to capture the wider elements of fuel poverty, and focus on social exclusion and material deprivation, as opposed to approaches based solely on expenditure-based indicators. In the literature, we found cases where people can be fuel poor and not monetarily poor. Legendre and Ricci (2015), studied a sample of individuals above the monetary poverty line that fell into poverty after paying their energy bill. This sub-sample represents 2.76% of the non-poor before energy expenditures. Identifying these people is possible as the relative poverty rate in developed countries is calculated using disposable income per consumption unit before expenditures on food, clothes or energy. Consequently, creating the measure *house poor* appears particularly useful as it enables the identification of one particular source of precariousness. Knowing the source of precariousness makes it possible to design an appropriate policy to improve the standard of living and well-being of the population.

Moreover, in some dwellings, real heating energy consumption is systematically lower than theoretical consumption (on average 30% lower), which is assumed to be explained by restriction behavior. This is the concept of the *prebound effect* ([Galvin 2014](#)). The *prebound effect* suggests that policymakers who want to implement energy efficient initiatives may be over-estimating the benefits, and the rate of pay-back can be exaggerated due to restriction behavior and potential energy savings.

So, in the context of fuel poverty, being deprived of basic household utilities should be considered an indicator of fuel poverty in a unified social approach.

2.2 Construction of the Fuel Poverty Index (FPI)

Pioneering poverty specialists such as [Sen \(1979\)](#) recommended considering multiple dimensions to identify who the poor are. The report [European Fuel Poverty and Energy Efficiency \(2006\)](#) shows that fuel-poor households have several common characteristics: the inability to pay energy bills, cold and damp living conditions, debt, homes with low energy performance, and disconnection from energy supply. The consequences of these conditions are numerous, and sometimes the cost/income function approach is irrelevant: low-income households coping with financial constraints reduce their energy expenditures as a primary strategy. Spending on energy is usually reduced by cutting consumption ([Anderson, White, and Finney 2012](#), [Moore 2012](#)) especially by reducing the use of heating, which we will refer to as

restricted heating. Overall, the notion of privation appears relevant to characterizing poverty, which is particularly consistent with the analysis of fuel poverty. Despite the recommendation of many European organizations to take restricted heating into account in ensuring basic needs are met, policymakers generally use monetary definitions to identify fuel-poor households. Thus, considering restriction behavior seems quite relevant in the study of fuel poverty.

The advantages of a composite indicator that compares fuel poverty level across households have been increasingly recognized in policy analysis ([ONPE 2014](#)). Such an indicator is a useful tool in identifying trends and drawing attention to particular issues. One of the main advantages of a composite indicator is its ability to capture multidimensional concepts that cannot be appraised by a single indicator, while being easier to interpret than a battery of many separate indicators. Thus, we propose a composite indicator that can allow for the three indicators from the EU SILC⁴ but in a normative way. Instead of just analyzing answers to questions, as in the SILC survey, we developed a multidimensional numeric index, the fuel poverty index (FPI), to capture these three aspects of fuel poverty. This index is based on geometric means and considers 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), which implies that all variables are equally considered in the indicator. This assumption seems justified in the absence of proof of an alternative. The composite fuel poverty index (FPI) is expressed as:

$$FPI(P.C.R) = \sqrt[3]{I_p \times I_c \times I_R} \quad [4]$$

where I_p is an indicator of standard of living, I_c an indicator of the housing energy inefficiency and I_R captures the potential heating restriction by providing information about housing temperature. I_p , I_c , I_R allow comparisons of household attributes to objective references in the three dimensions.

⁴ Three indicators from the EU SILC dataset have been commonly used to capture aspects of EU fuel poverty: living in a damp home, inability to keep adequately warm, and being in arrears on utility bills: cf. ([Devalière 2007](#), [European Fuel Poverty and Energy Efficiency 2011](#), [Waddams Price, Brazier, and Wang 2012](#), [ONPE 2014](#)) These variables correspond to the fuel poverty dimensions we have identified: monetary constraints, energy inefficiency, and restricted heating. Unfortunately, often only low income/high costs and the energy-income ratio are used in fuel poverty analysis. We proceeded as follows in constructing the energy poverty index: First, the choice of dimensions in the indicator is micro-funded based on Welsch, H. and P. Biermann, 2017. Second, we drew from the handbook of composite indicators from the European Commission and OECD, 2008 in construction of the index. Finally, selection of a suitable method is not trivial and deserves special attention with respect to eventual scale adjustment ([Ebert and Welsch 2004](#)). For this reason we conducted some robustness tests in line with the recommendations of the [European Commission and OECD \(2008\)](#).”

Equation [4] enables us to consider the complementarity between the three dimensions across a geometric aggregation: the elasticity of the FPI in each dimension cannot be separated from the other two. Indeed, an objectionable consequence of additive aggregations is that poor performance in one dimension can be compensated with high values in other dimensions. The geometric mean reduces the level of substitutability between dimensions and at the same time ensures that a 1% decline in the index of restricted heating has the same impact on the FPI as a 1% decline in the income index. Thus, as a basis for comparison of achievement, this method is also more sensitive to the intrinsic differences across the dimensions than a simple average. If multi-criteria analysis entails full non-compensability, the use of a geometric aggregation is a solution ([European Commission and OECD 2008](#)). Moreover, in this study, a Min-Max normalized indicator is retained by subtracting the minimum value and dividing by the range of the indicator values. While there are several possible normalization methods ([Freudenberg 2003](#), [Jacobs, Smith, and Goddard 2004](#)), they should be chosen based on data properties as well as the objectives of the composite indicator. Thus, sensitivity analyses are provided in part 5.2 to ensure the robustness of the indicator and the choice of the Min-Max normalization.

First, monetary poverty is captured through I_p :

$$I_p = \frac{P - \text{Min}(P)}{\text{Max}(P) - \text{Min}(P)} \quad [5]$$

where P is the ratio between the poverty threshold, set at 60% of the median per consumption unit (PCU)⁵ disposable income, and the household PCU disposable income.

Energy per square meter consumption (C) is used to calculate I_C :

$$I_C = \frac{C - \text{Min}(C)}{\text{Max}(C) - \text{Min}(C)} \quad [6]$$

Finally, we measure heating restriction. The restriction behavior measure stands out from other previous monetary approaches but still belongs to the group of objective measures. It is often based on the calculation of both the actual and theoretical fuel consumption needed to reach an appropriate level of warmth in a dwelling. As mentioned previously, considering theoretical measures of consumption does not seem appropriate for France ([Allibe 2012](#)). One issue is the quality of the energy performance diagnoses made by professionals, who do not necessarily

⁵ Consumption per household member.

have the skills to perform accurate diagnoses. Moreover, there is no regulation of the professionals who prescribe and install equipment. Not all information is available and therefore assumptions must be made about certain aspects of energy efficiency, such as the quality of wall insulation. Finally, theoretical energy consumption does not consider the number of persons or the number of appliances in the dwelling. The strengths of a composite fuel poverty indicator largely derive from the quality of its underlying variables ([European Commission and OECD 2008](#)). Thus, one difficulty lies in the objective measurement of privation. The concept of restricted heating can be very subjective and relative if it is not rigorously observed. 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](#)). The World Health Organization [WHO \(1987\)](#) recommends an indoor temperature of 21 degrees Celsius in living areas and has demonstrated the consequences of insufficient temperatures on health ([Ormandy and Ezratty 2012](#), [Lacroix and Chaton 2015](#)). Considering these findings, we propose indoor temperature as an objective measure of restricted heating. One solution to measure heating privation is to compare effective indoor temperatures to those recommended. The calculation of the last indicator is based on this recommendation:

$$I_R = \frac{R - \text{Min}(R)}{\text{Max}(R) - \text{Min}(R)} \quad [7]$$

where

$$R = \frac{21}{\text{housing mean temperature}} \quad [8]$$

In order to demonstrate that indoor temperature is a good proxy for heating privation, we provide some evidence in Appendix A using an econometric analysis involving matching methods. Some proofs of the quality estimate are also provided.

It is clear that poor energy efficiency in housing does not have the same consequences for low-income households as it does for rich ones, since wealthy households have the means to undertake energy-efficiency renovations. The advantage of the FPI index is to provide a scale rather than simply defining households as fuel-poor or not. While the problem of using an index is that the values generated have little intrinsic meaning, it is still a better way to classify who suffers the most from fuel poverty in France. It is then up to the policymaker to decide which population at which ranges of the FPI index needs to be targeted with specific policies.

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

Finally, while several decisions must be made when a composite indicator is constructed (on the selection of indicators, data normalization, weights, and aggregation methods), the sensitivity analyses provided in section 4.3 confirm the robustness of the FPI.

3. Data

This study uses French data based on the PHEBUS (survey on housing performance, equipment, needs, and uses of energy) database. This new periodic survey consists of two parts administered separately: a face-to-face interview with the occupants of the home about their energy consumption expenditures and attitude, and an energy performance diagnosis of the housing⁶. The survey aims to provide information about the energy performance of the housing stock, allowing for analysis according to household characteristics and appliances, as well as energy use and energy consumption. It was implemented to understand the drivers of energy consumption in France for the purpose of adapting public policy.

This survey is very interesting because it provides highly detailed information on energy consumption by type of fuel, energy costs and energy rates. Information is also available on the renovations undertaken by households, incentives to renovate (energy savings or improved comfort), and public policies. Moreover, a large part of the survey is devoted to the behavior of households and their satisfaction with their heating system, so it is possible to know if households restrict their energy use and what their preferences are. We know whether households prefer to achieve energy savings or comfort in their homes by end-uses, namely, by making a distinction between consumption of 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 whether households restrict their consumption

⁶ 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, along with asbestos diagnostics, termites, lead, and status of indoor facilities for electricity and gas. This diagnosis has been mandatory since November 1, 2006 in case of sale of a dwelling and since July 1, 2007 for leasing. The display of the energy performance of real estate in the real estate agencies has been mandatory since January 1, 2011. The diagnosis is provided free to the respondent at the end of the investigation and has a 10-year validity period.

by reducing the temperature or by choosing not to heat some rooms. Finally, we know if households have a sense of discomfort and what the source of this feeling is.

Considering all these factors, we can therefore conduct a thorough analysis of fuel poverty taking into account not only monetary variables but also household and building characteristics as well as heating restriction. More subjective questions on satisfaction in terms of heating are also available. This study also makes it possible to study fuel poverty with information not only on disposable income but also on energy expenditures and attitude towards energy consumption (through temperature). To our knowledge, such an interesting and detailed database is rare in France. Our sample contains 2,318 households and is representative of the population (the sample is weighted to ensure representativeness).

Some descriptive statistics are presented in Table 1. In general, energy consumption is higher in old buildings and in the coldest climate zone, which is not surprising. One interesting result has been obtained for the fuel poor according to the AFCP definition: their energy consumption is lower than the average and they have a low indoor temperature, which highlights restriction behavior. This group is also poorer than those in other fuel-poor categories.

To measure fuel poverty, we examined the multiple aspects of fuel poverty in France using three different measurement approaches: the 10% ratio approach (energy-income ratio), the LIHC approach and the AFCP approach. Descriptive statistics are also presented in Table 2.

Table 1 Main descriptive statistics 1

	Effective Energy Consumption (kWh/m ² /year)	Temperature	Disposable income
Individual housing units	186.02	19.90	40962
Collective building	120.37	20.13	32280
Dwelling constructed before 1919	196.06	19.63	35068
Dwelling constructed between 1919 and 1945	184.64	19.80	36288
Dwelling constructed between 1946 and 1970	161.97	20.07	36032
Dwelling constructed between 1971 and 1990	150.57	20.15	38090
Dwelling constructed between 1991 and 2005	157.74	20.01	43092
Dwelling constructed after 2005	139.24	19.95	42764
Dwelling located in climate zone H1 (coldest zone)	172.88	20.12	39493

Dwelling located in climate zone H2 (middle zone)	160.10	19.66	35744
Dwelling located in climate zone H3 (Mediterranean zone)	121.77	20.21	37281
Possible to change the indoor temperature in the dwelling	168.86	19.89	39269
Not possible to change the indoor temperature in the dwelling	144.50	20.35	33085
Boiler system installed before 1986	223.28	19.99	36323
Boiler system installed between 1987 and 1991	223.76	19.92	40600
Boiler system installed between 1992 and 1996	222.21	20.04	41104
Boiler system installed between 1997 and 2001	198.28	19.90	39869
Boiler system installed between 2002 and 2006	213.41	19.94	43450
Boiler system installed between 2007 and 2012	188.16	19.81	40362
Dwelling with a cooling system	218.59	20.02	31883
Dwelling without a cooling system	166.20	19.94	37673
Dwelling occupied by fuel poor (energy income ratio)	278.3	19.82	18760
Dwelling occupied by fuel poor (AFCP)	162.05	19.79	16979
Dwelling occupied by fuel poor (LIHC)	203.68	19.91	18531
Means	164.12	19.98	38066

Table 2 Main descriptive statistics 2

Variables	Means (with weight) in Euros
Disposable income	38,066
Disposable income by u.c.	23,589
Annual housing costs for tenants or rent-free occupants	5,839
Housing costs for homeowners or first-time buyers	3,724
Total housing costs	4,229
Household disposable income - housing costs	35,005
Household disposable income - housing costs in u.c.	21,534
Effective (or real) energy expenditures for electricity	769
Effective energy (or real) expenditures for gas	968
Effective energy (or real) expenditures for oil	1,633
Effective energy expenditures for coal	974
Total effective (or real) energy expenditures	1,464
Total effective energy (or real) expenditures by u.c.	949
Disposable income – housing costs and energy expenditures by u.c.	33,526

We found the energy-income ratio to be equal to 0.0516⁷, while the same ratio calculated between energy expenditures and disposable income after housing costs and domestic fuel costs increased to 0.0571. The three definitions of fuel poverty identify quite different fuel poverty rates in France: 9.16% of the population are fuel poor according to the 10% ratio approach, 9.16% according to the LIHC approach, and 18.07% according to the AFPC approach.

4. Results

4.1 Fuel poverty and household profile

We conducted *t*-tests (Table B-1 in Appendix B) to identify household profiles according to the definition of fuel poverty,. For continuous variables, particularly FPI, indoor temperature, and energy consumption, we conducted correlation tests. There is a strong correlation (significant at 1%) between FPI, low indoor temperature, and high energy consumption.

Table 3 Profiles of the fuel poor by indicator

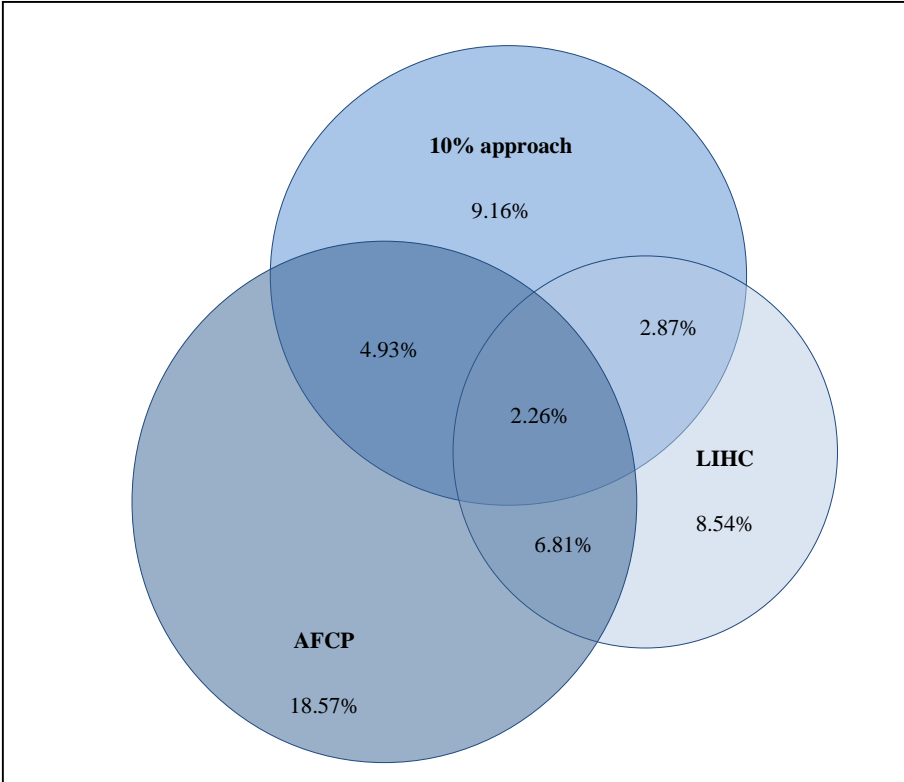
10%	AFPC	LIHC	FPI
Household characteristics			
Low income	Low income	Low income	Low income
Tenant	Tenant	Tenant	Tenant
Possible to adjust the heating	Possible to adjust the heating	Possible to adjust the heating	Possible to adjust the heating
Preference for heating comfort	Preference for heating comfort	Preference for heating comfort	Preference for heating comfort
Building characteristics			
High energy consumption	High energy consumption		High energy consumption
Old building	Old building	Old building	Old building
Location			

⁷ This means that energy expenditures represent 5.16% of a household's disposable income.

Coldest climate zone		Coldest climate zone	Coldest climate zone
Heating restriction			
	Low temperature		Low temperature
Report restricting heating consumption by cutting or sharply reducing heating	Report restricting heating consumption by -cutting or sharply reducing heating	Report restricting heating consumption by -cutting or sharply reducing heating	Report restricting heating consumption by: -cutting or sharply reducing heating
	-limiting the number of heating weeks in the year	-limiting the number of heating weeks in the year	-limiting the number of heating weeks in the year
	-limiting the heating time during the day	-limiting the heating time during the day	-limiting the heating time during the day
	-not heating some rooms	-not heating some rooms	-not heating some rooms
	-using auxiliary heater instead of main heater	-using auxiliary heater instead of main heater	-using auxiliary heater instead of main heater
Subjective measure of fuel poverty			
			Cold discomfort due to:
			-Financial reasons
			-Insufficient heating installation
			-Bad insulation
			-Unpaid power provider
			-Power supply shutdown
			-Wrong setting
			-Harsh winter

Standard measures of fuel poverty miss households who are at around a certain threshold, but who are not necessarily fuel poor. ([Charlier, Risch, and Salmon 2015](#)): When we combine definitions, different households are included. Only 2.26% of households are fuel poor if we combine the three usual measures. Indeed, according to the definition, the profile of the fuel-poor households is different. In the 10% approach, low indoor temperature and thermal discomfort are not included. The AFCP also includes these subjective measures and location (a proxy for energy needs). The LIHC, on the other hand, does not include poor energy efficiency of dwellings, measured by high energy consumption (and confirmed by the absence of a low indoor temperature), or subjective measures of fuel poverty.

Figure 1: Fuel poverty as captured by standard measures



These results show that one advantage of the FPI is that it considers all dimensions of fuel poverty, especially heating restriction and subjective measures such as thermal discomfort.

4.2 Comparison of FPI to other measures (10%, LIHC, AFCP)

We found that 75% of the population has an FPI value lower than 0.126 and 99% has a value lower than 0.206. Table 4 summarizes the various components of the composite fuel poverty index, which is 0.107 in France.

Table 4 FPI index and its three dimensional indicators

	(weighted) Mean	Min	Max
<i>P</i>	0.69	0.05	3.93
<i>C</i>	164.1	0.00	3126.94
<i>R</i>	1.06	0.165	2.63
<i>I_p</i>	0.186	0.00	1.00
<i>I_c</i>	0.052	0.00	1.00
<i>I_r</i>	0.107	0.00	1.00
<i>FPI</i>	0.13	0.00	0.44

We note that both the 10% and LIHC fuel poverty definitions encompass very similar household profiles. According to the 10% definition, *I_c* (energy inefficiency as expressed in energy consumption per square meter) reaches about 0.0890 for the poor, which is 70% (0.0776/0.0469) higher than for the non-poor. For the fuel poor according to the LIHC approach, *I_c* is only 27% higher than for the non-poor. By contrast, according to the AFCP approach, *I_c* for the poor represents only 98% of the indicator for the non-poor. The statistics presented in Table 5 confirm that the AFCP definition is very close to a definition of monetary poverty. The indicator of financial hardship, *I_p*, is indeed 86% higher for the poor than for the non-poor, whereas the difference between the poor and the non-poor is only 62% according to the LIHC definition.

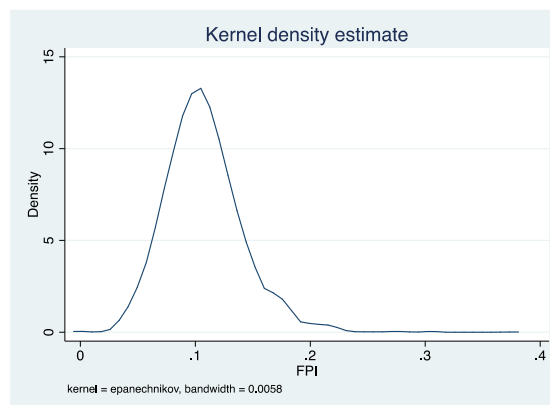
Table 5 FPI and other fuel poverty measures

Fuel poor as defined by	Not fuel poor
-------------------------	---------------

	10%	LIHC	AFCP approach	10%	LIHC	AFCP approach
I_p	0.2574	0.2923	0.2540	0.1538	0.1529	0.1451
I_c	0.0890	0.06513	0.0518	0.0522	0.0513	0.0526
I_r	0.190	0.1913	0.192	0.1876	0.1853	0.1844
FPI	0.1504	0.1429	0.125	0.1060	0.1041	0.1035

Figure 2 shows the population distribution according to FPI values. Compared with other fuel poverty measures, the 10% definition seems to better include those who combine relative financial hardship with relatively high energy consumption/m² (Table 5 and confirmed in Table 1). I_p and I_c are higher for this population than they are for the fuel poor according to the two other definitions. Relative restricted heating is the highest for the fuel poor defined according to the AFCP approach.

Figure 2 Kernel density estimate of FPI



To demonstrate that the FPI is an adequate measure of fuel poverty, we compared the three dimensions that a relevant definition should take into account ([European Fuel Poverty and Energy Efficiency 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.

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 poor
<i>Poor according to the 10% definition</i>					
1	0.057	34468	20	38.7	0.6%
2	–	–	–	–	0%
3	0.087	18782	17.9	55.0	0.8%
4	–	–	-	-	0%
5	0.102	20842	21.43	175.4	1.5%
6	0.107	19225	22.0	210.8	3.3%
7	0.116	18382	20.0	165.4	5.9%
8	0.125	16543	20.0	180.5	8.9%
9	0.140	15507	20.2	254.5	17.4%
10	0.176*	12349	19.5	331.8	45.4%**
<i>Poor according to the LIHC</i>					
1	0.057	12980	21.3	21.7	2.8%
2	0.074	14304	21.3	40.0	4.3%
3	0.087	12516	21.5	64.8	1.6%
4	0.094	10475	20.1	53.2	4.0%
5	0.101	9583	20.5	59.1	1%
6	0.109	14219	20.8	120.7	5.5%
7	0.115	16042	21.5	180.9	3.7%
8	0.125	13408	20.8	169.5	10.1%
9	0.139	13104	19.5	187.8	11.2%
10	0.176	10387	19.2	282.2	39.2%
<i>Poor according to the AFCP approach</i>					
1	0.059	15383	20.7	20.6	11.9%
2	0.075	16895	19.9	42.4	10.6%
3	0.086	18209	19.9	66.6	6.3%
4	0.095	16750	19.9	81.7	13.2%
5	0.101	16193	20.2	100.8	9.2%
6	0.109	15127	20.1	113.4	19.6%
7	0.115	17023	20.3	157.5	17.0%
8	0.126	13327	20.1	162.8	23.1%
9	0.139	12808	19.3	179.5	22.1%
10	0.175	10749	19.2	285.0	45.7%

<i>FPI of the total sample</i>				
1	0.056	37594	20.7	48.5
2	0.076	28684	20.3	80.3
3	0.086	29878	20.2	117.9
4	0.094	26399	20.0	129.1
5	0.101	23890	19.9	146.8
6	0.108	21522	19.9	159.4
7	0.116	20172	19.9	183.4
8	0.125	18029	19.8	197.9
9	0.139	16792	19.6	242.2
10	0.173	12462	19.2	336.5

Note: According to the *10% ratio* definition, the 10% with the highest FPI have an average index of 0.173. **Moreover, 45.4% of the fuel poor belong in the highest decile of FPI.

Looking more precisely at the FPI and other monetary definitions of fuel poverty, the most interesting result is related to disposable income. The results show that the FPI truly takes into account dimensions other than just monetary constraints. For example, the FPI shows nonlinear effects of income: Households can have a high FPI (in the 10th decile) and a somewhat higher standard of living than that of the fuel poor, on average 12,462 euros for all households in the 10th decile of FPI and less than 10,749 euros for the fuel poor according to two definitions of fuel poverty in the 10th decile of FPI.

The similarity of both the AFCP and LIHC definitions is confirmed in Table 6: profiles of the poor according to both definitions appear quite close together within the 10 deciles of FPI. The standard of living for the fuel poor, according to those definitions, reaches about 10,387 euros in the 10th decile, with an indoor temperature of about 19.2°C, and annual energy consumption levels of 285 and 282 kWh respectively per m². Eventually, almost 90% of the fuel poor according to the AFCP definition belong to the three highest deciles of FPI and 70% for the 10% approach, while the LIHC approach places only 60% of the fuel poor in this area.

The FPI has the distinct advantage of including all the dimensions of fuel poverty, which was not the case for previous fuel poverty definitions. It provides a scale of fuel vulnerability rather than simply a binary indicator. « It is now up to policymakers to adapt energy surveys so that FPI can help make comparisons over time and countries. However, this measurement should be associated with the roll-out of smart metering in industrialized countries. Numerous studies have demonstrated that improving information on energy consumption can lead to energy efficiency

gains ([Arrow and Fisher 1974](#), [Ehrhardt-Martinez, Donnelly, and Laitner 2010](#), [Brounen, Kok, and Quigley 2013](#), [Pon 2017](#), [Wolak 2011](#), [Di Cosmo, Lyons, and Nolan 2014](#), [Jesso and Rapson 2014](#), [Carroll, Lyons, and Denny 2014](#), [Matsukawa 2004](#), [Grimes et al. 2016](#)). Moreover, smart metering can be also considered as a tool to fight climate change and to identify which households restrict their heating consumption.

4.3. Sensitivity analysis

As mentioned previously, the indicators, data normalization techniques, weights, and aggregation methods used to construct a composite indicator can be controversial. In the case of the fuel poverty index, the selection of indicators is fairly consensual ([ONPE 2014](#)), as is the choice of a geometric mean to avoid error measurement (due to the exclusion of one dimension). Thus, in this study, we provide some robustness and sensitivity analyses to assess the robustness of the fuel poverty composite indicator in terms of the mechanism for calculating single indicators, the normalization scheme, and the removal of extreme value data. Indeed, we can refine both the sensitivity analysis and the standardization of basic indicators by considering the minimum and maximum values set for the poverty and restricted heating dimensions. 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 previously obtained results. If the values are quite similar, the composite indicator shows the importance of considering three dimensions with a similar weight. This can prevent errors in measurement of fuel poverty due to changes in indicator, for example.

We proposed different sensitivity analyses to assess whether our composite indicator is robust in all three dimensions. Statistical analysis can demonstrate also the precision of the data⁸. We first conducted sensitivity analyses to extreme values (Table 7): Observations for the population with the 5% lowest and highest value for each dimension separately were removed. The results of the FPI were also compared with sensitivity to the poverty threshold and the reference temperature set by the WHO (Table 8).

Table 7 Sensitivity analysis of extreme values

⁸ This is true whatever the purpose of the paper and the science discipline. See for example papers in science such as ([Taner 2015](#), [Taner and Sivrioglu 2015](#))

Percentile of FPI	Without extreme values* for PCU disposable income	Without extreme values* for temperature	Without extreme values* for consumption	Without extreme values* for FPI
1	0.0507	0.0567	0.0593	0.0644
2	0.0756	0.0754	0.0757	0.0755
3	0.086	0.0857	0.0857	0.0856
4	0.0937	0.0937	0.0937	0.0937
5	0.1010	0.1009	0.1010	0.1010
6	0.1085	0.1086	0.1085	0.1085
7	0.1163	0.1162	0.1162	0.1162
8	0.1256	0.1257	0.1257	0.1257
9	0.1384	0.1384	0.1386	0.1386
10	0.1684	0.1717	0.1690	0.1627
Means	0.1047	0.1066	0.1089	0.1082

Note: We remove the 5% of the population whose values are the lowest and 5% of the population whose values are the highest.

Table 8 Sensitivity analysis of 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	3.93	3.27	-
R	1.06	-	1.01
R min	0.7	-	0.67
R max	2.63	-	2.50
<i>I_p</i>	0.165	0.165	0.165
<i>I_c</i>	0.052	0.052	0.052
<i>I_r</i>	0.186	0.186	0.185
<i>FPI</i>	0.107	0.107	0.107

Results show that the fuel poverty composite indicator continues to be around 0.107 even when 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 though the minimum and maximum values change in one indicator, the overall results are not affected. The FPI is also robust to outliers. Our methodology is thus robust and useful for classifying fuel poverty in households.

5. Conclusion and policy implications

Fuel poverty is an increasingly serious problem across countries but remains a concept that is not very well defined or measured. Even though there is a fairly clear understanding of living conditions and relative poverty, a clear definition of fuel poverty has not yet emerged. Thus, the major original feature of this paper is to provide the first fuel poverty index that takes into account the three dimensions of fuel poverty: monetary constraints, poor residential energy efficiency, and heating privation. Standard measures of fuel poverty reveal a gap that does not consider all the dimensions of fuel poverty. The advantages of proposing a composite indicator that compares fuel poverty level across households are increasingly recognized in policy analysis. Today, many households are excluded from the usual definitions of fuel poverty if we consider subjective measures such as thermal discomfort or heating restriction, and are not thus well targeted by policymakers. The FPI enables us to correct this shortcoming and constitutes a new decision-making tool with many advantages.

First, the FPI index provides a scale rather than simply defining households as fuel poor or not. It offers policymakers the possibility of choosing which population at which ranges of the FPI index need to be targeted with specific policies. Moreover, by allowing a dynamic comparison over time, the FPI can be viewed as a fuel poverty monitoring indicator to be used in evaluating public policy. For instance, a decrease in the FPI would lead us to perceive a decline in fuel poverty in general. In particular, it is now possible to identify in which dimension (monetary, energy efficiency, or heating restriction) a given policy is the most effective.

Finally, this index can be used to make comparisons not only among households inside a country, but also, once aggregated, among countries. In order to apply the FPI internationally, however, better data collection techniques are needed to compare household situations. While it may be time- and cost-effective to include subjective statements such as “I have difficulty keeping my home adequately warm” in the survey of Income and Living Conditions (EU-SILC), we can hope that the quality and precision of the fuel poverty composite indicator will improve in parallel with improvements in data collection and fuel poverty measurements. Governments should provide further incentives to make these improvements to enhance the international comparability of these statistics. It is now up to policymakers to adapt their energy surveys so that FPI can be calculated to make comparisons over time and countries.

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Appendix

A. Measure of restricted heating: An econometric estimate

A.1 Model

To measure the impact of restricted heating, it is necessary to evaluate the difference in an outcome variable. We selected the mean housing temperature to verify if the restriction leads to objective differences among households who do not declare a restriction in their heating energy consumption.

Potentially constrained households are denoted as i . A vector x of control variables represents their personal attributes and housing characteristics. The binary variable (the treatment variable) denoted R , reports whether the household reports restraining its heating energy consumption. For the treated sample, we have $R = 1$, and for the control group, $R = 0$.

Only a perfectly randomized evaluation makes it possible to avoid selection bias in the estimate. In that case, comparing the difference in the outcome variable between treated and untreated individuals provides the impact of the treatment ([Rubin 1974](#)). However, in most cases, independence between the probability of being treated and personal attributes cannot be assumed. In our case, restricting heating energy consumption is undoubtedly strongly linked to household characteristics, including housing conditions. The present study is based on non-experimental data. We therefore used a non-experimental method to estimate the impact of the heating consumption constraint. The impact of heating restriction ($\beta(x)$) should ideally be the difference between the outcome variable for the treated households (Y_1) and this variable if the household had not been treated (Y_0):

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

[9]

where:

$$Y = RY_1 + (1 - R)Y_0 \tag{10}$$

Y_0 and Y_1 cannot be observed simultaneously, so the counterfactual temperature must be calculated. We used matching estimators, which requires matching each constrained household with one or many unconstrained households. [Rubin \(1974\)](#) proposed matching observations on observable characteristics. Under the assumption that the 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 was matched to an unconstrained household based on the probability of being constrained, conditionally on the different observed characteristics x . This conditional probability is the propensity score (Rosenbaum and Rubin

(1983). Matching on $R(x)$ is as good as matching on x ([Rosebaum and Rubin \(1983\)](#)). Key assumptions for identifying the constraint effect are conditional independence—or *unconfoundedness* ([Rosebaum and Rubin 1983](#))—and the presence of a common support for propensity score density ([Heckman, Lalonde, and Smith 1999](#)). Under these assumptions, the propensity score matching average treatment is then equal to the mean difference in temperature over the common support.

We first performed one of the most frequently used matching techniques, nearest neighbor (NN) matching, and matched the treated observations with the five closest controls. This estimator implies a comparison between each treated unit 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 for constructing the counterfactual outcome. For this reason, nonparametric matching estimators such as kernel matching were used to construct a counterfactual match for each treated unit by using the weighted average of all untreated units. The weights ($\omega(\cdot)$) for kernel matching are given by:

$$\omega(i, j) = \frac{K\left(\frac{P_j - P_i}{a_n}\right)}{\sum_{k \in C} K\left(\frac{P_k - P_i}{a_n}\right)} \quad [11]$$

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). $K(\cdot)$ is a kernel function and a_n a bandwidth parameter. Robust standard errors were calculated using bootstrap as the estimators are asymptotically linear ([Imbens 2003](#)). Bootstrapping standard errors also enabled us to take into account the variance due to derivation of the propensity score matching and determination of the common support ([Heckman, Ichimura, and Todd 1997](#), [Efron and Tibshirani 1993](#), [Horowitz 2003](#)). The variables used for analysis are presented in the next section.

A.2 Variables used in the matching estimate

We balanced both subsamples (treated and untreated) by using dummy variables of income percentiles, homeownership, and size of the urban area. We also included a binary variable capturing whether the household can adjust its heating energy consumption, as this is not possible in some collective housing. The housing characteristics were introduced with the

construction period and the energy consumption classification, estimated by a professional agency, indicating if the housing is energy efficient. The energy classification label, from A-G, provides insight into the energy efficiency of the dwelling: The A label is the most energy efficient, while the G label is the least efficient. The database provides the energy label for each dwelling.

Finally, one way to measure household preferences is measured through the answer to the question “Do you prefer reaching your comfort temperature or saving on heating costs?” Even if this question is relative to quality of life, it is a way to measure the ranking of thermal comfort in the hierarchy of household preferences.

Urban area categories include: rural areas (urban area size 0), areas with 2,000 to 9,999 inhabitants (urban area size 1), areas with 10,000 to 99,999 inhabitants (urban area size 2), areas with 100,000 to 1,999,999 inhabitants (urban area size 3), and Paris (urban area size 4).

Including construction periods enabled us to control for thermal performance, as current thermal regulations were implemented in the 1970s. Finally, we had to ensure that the sense of restricted heating declared by the treated observations did not come only from a strong preference for heat, so we included the preference variable. Variables are summarized in Table A-1.

Table A-1 Summary statistics according to heating restriction

	All sample		Unrestricted households		Restricted households	
	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Percentile 1	0.1730	0.3783	0.1474	0.3546	0.2643	0.4414
Percentile 2	0.1838	0.3874	0.1756	0.3806	0.2130	0.4098
Percentile 5	0.2312	0.4217	0.2590	0.4382	0.1321	0.3390
Percentile 4	0.2187	0.4135	0.2258	0.4183	0.1933	0.3953
Age	55.6946	15.3273	55.9028	15.4837	54.9507	14.7457
Homeowner	0.7472	0.4347	0.7780	0.4157	0.6371	0.4813
Possible to adjust the heating	0.8197	0.3845	0.8073	0.3945	0.8639	0.3432
House	0.7274	0.4454	0.7355	0.4412	0.6982	0.4595
Urban area size 0	0.2558	0.4364	0.2662	0.4421	0.2189	0.4139
Urban area size 1	0.1230	0.3285	0.1209	0.3261	0.1302	0.3368
Urban area size 3	0.1915	0.3936	0.1839	0.3875	0.2189	0.4139
Urban area size 4	0.1311	0.3376	0.1314	0.3380	0.1302	0.3368

Preference for saving heating costs	0.4055	0.4911	0.3054	0.4607	0.7633	0.4255
Construction period: after 1971	0.5626	0.4962	0.5743	0.4946	0.5207	0.5001
DPE classification A or B	0.0237	0.1522	0.0265	0.1607	0.0138	0.1168
Heating restriction	0.2187	0.4135				
Observations	2.318		1.811		507	

These first descriptive statistics suggest that restricted heating is linked to occupation status and preferences for saving heating costs. Housing also seems to be less energy efficient among households who restricted their energy consumption.

A.3 Results

A.3.1 First step

In our two-step analysis, we first calculated the propensity scores (the probability of being constrained). The probability of restricting heating energy consumption is significantly influenced by standard of living, homeownership, whether it is possible to adjust the heating, preference for heating cost savings, and construction period. These results are in line with [Healy and Clinch \(2002\)](#), [Healy \(2003\)](#). Being a homeowner of a recent residence and belonging to the highest percentile seems to protect against restricted heating. However, being able to adjust the heating system has a positive and significant impact. On average, the literature reports that having a collective boiler or being linked to a district heating system prevents more fuel poverty as previously defined.

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

Table A-2 Estimate of the propensity scores

	Coeff.	Standard errors
Percentile 1	0.235**	(0.102)
Percentile 2	0.0607	(0.101)
Percentile 5	-0.334***	(0.105)
Percentile 4	-0.0412	(0.0997)

Age	-0.000602	(0.00214)
Homeowner	-0.245***	(0.0810)
Possible to adjust the heating	0.377***	(0.0890)
House	0.0553	(0.0882)
Urban area size 0	-0.0491	(0.0908)
Urban area size 1	0.0300	(0.107)
Urban area size 3	0.0226	(0.0922)
Urban area size 4	0.0710	(0.110)
Preference for comfort for heating	-1.051***	(0.0650)
Construction period: after 1971	-0.0885	(0.0642)
DPE classification A or B	-0.336	(0.251)
Constant	-0.366**	(0.179)
Log likelihood	-1022.55	
No observations	2318	

*** Significant at 1%. ** significant at 5%. * significant at 10%

After matching, we checked the balancing property. It is necessary to ensure that the household characteristics of the control and treated groups are comparable after matching (Table B-2 and Table B-3). Thus, two indicators are commonly used: the standardized percentage bias and the propensity score estimates of explanatory variables ([Rosenbaum and Rubin 1983](#)). The overall bias decreases significantly after matching, from 9.2% to 1%.

Table A-3: Matching quality 1

Heating preference for comfort		
	Standardized percentage bias	LR χ^2
Before matching	9.5%	415.5
After matching	1.7%	$p > \chi^2 = 0.000$ ***

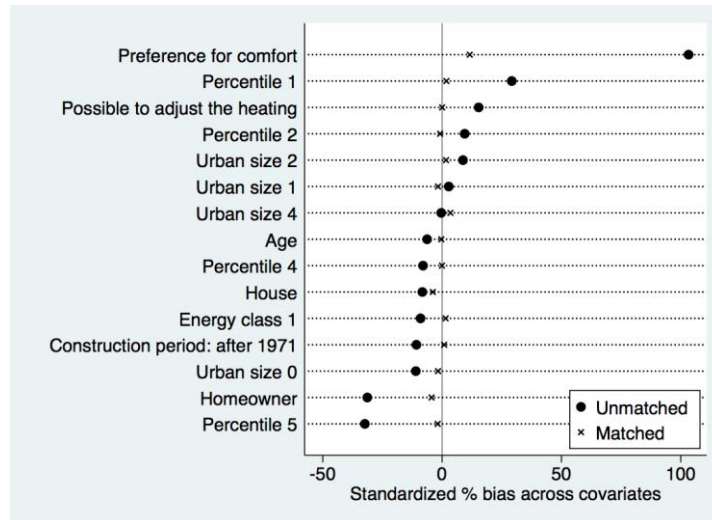
Table A-4: Matching quality 2

Variable	Unmatched	Mean		% bias	% reduct. bias	t	p>t
	Matched	Treated	Control				
Percentile 1	U	0.2643	0.14743	29.2		6.20	0.000

	M	0.25992	0.25277	1.8	93.9	0.26	0.795
Percentile 2	U	0.21302	0.17559	9.5		1.92	0.054
	M	0.21429	0.21758	-0.8	91.2	-0.13	0.899
Percentile 5	U	0.13215	0.25897	-32.4		-6.03	0.000
	M	0.13294	0.14017	-1.8	94.3	-0.33	0.738
Percentile 4	U	0.19329	0.22584	-8.0		-1.57	0.117
	M	0.19444	0.1947	-0.1	99.2	-0.01	0.992
Age	U	54.951	55.903	-6.3		-1.24	0.216
	M	55.075	55.127	-0.3	94.6	-0.05	0.957
Homeowner	U	0.63708	0.77802	-31.3		-6.51	0.000
	M	0.64087	0.66073	-4.4	85.9	-0.66	0.509
Possible to adjust the heating House	U	0.86391	0.80729	15.3		2.94	0.003
	M	0.8631	0.86307	0.0	100.0	0.00	0.999
Urban area size 0	U	0.69822	0.73551	-8.3		-1.67	0.096
	M	0.69643	0.71405	-3.9	52.7	-0.61	0.540
Urban area size 1	U	0.21893	0.26615	-11.0		-2.15	0.031
	M	0.22024	0.22748	-1.7	84.7	-0.28	0.783
Urban area size 2	U	0.13018	0.12093	2.8		0.56	0.575
	M	0.12897	0.13467	-1.7	38.3	-0.27	0.789
Urban area size 4	U	0.21893	0.18388	8.7		1.77	0.076
	M	0.21825	0.21167	1.6	81.2	0.25	0.799
Preference for comfort	U	0.13018	0.13142	-0.4		-0.07	0.942
	M	0.12897	0.11731	3.5	-839.2	0.56	0.574
Construction period After 1971	U	0.76331	0.30536	103.3		20.11	0.000
	M	0.7619	0.71062	11.6	88.8	1.85	0.065
Energy class 1	U	0.52071	0.57427	-10.8		-2.15	0.032
	M	0.52381	0.51958	0.9	92.1	0.13	0.893
	U	0.01381	0.0265	-9.0		-1.66	0.097
	M	0.01389	0.01182	1.5	83.7	0.29	0.771

Figure A-1 below shows that the deviation is largely reduced after matching. Before matching, the distribution of confounders was different between two groups (heating preference for comfort and heating preference for energy savings), while the residual imbalance between matched groups was almost negligible (standardized bias $\leq 1\%$ across all variables).

Figure A-1: Standardized percentage bias before and after matching



We also wanted to check the region of common support to see if we had enough overlap between the treatment and control groups to make reasonable comparisons. The “common support or overlap condition: $0 < P(T_i = 1|X_i) < 1$ ensures that treatment observations have comparison observations nearby in the propensity score distribution” ([Heckman, Lalonde, and Smith 1999](#)).

A.3.2 Second step

The second step consists of the calculation of temperature differentials using nearest-neighbor and kernel matching methods. The sensitivity of the results to a deviation from the assumption of conditional independence of potential outcomes (CIA) is presented in the sensitivity analysis section. Households reporting restricted heating live, on average, in less heated housing, or at least in slightly cooler housing. On average, the temperature in their residence is 0.46 to 0.49 degrees lower⁹ (Table 3).

Table A-5 Mean average treatment effect

	Average restriction effect	Robust standard errors
Nearest neighbor (5) matching	-0.4604762	0.10308***
Kernel matching	-0.4928	0.091068 ***

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

⁹ This result is confirmed when performing radius matching and stratification matching methods.

This result confirms that omitting restricted heating from the calculation of fuel poverty leads to an underestimation of the phenomenon. Considering that the average restriction influences temperature, a relevant fuel poverty measure should include not only monetary constraints, but also energy consumption (as a proxy of energy efficiency) and temperature to measure thermal privation. This could be a way to integrate a monetary aspect, an energy-efficiency aspect, and the aspect of well-being through mean temperature. The impact of restricted heating could be captured in a normative way. For this reason, we consider it necessary to develop a numeric index (FPI) capturing these three aspects of fuel poverty.

A.4 Sensitivity analysis after matching

Matching is based on the assumption that selection into the treatment group is only driven by observable factors, or the CIA.

This assumption has the main consequence that the choice of temperature is independent of the probability of restricting heating consumption. For more information about this assumption, see [Ichino, Mealli, and Nannicini \(2008\)](#). Results are presented in Table A-6 below. The first four columns contain the probabilities P_{ij} . For each value we give at U, the next two columns present, respectively, the outcome effect (i.e., the effect of u on the untreated outcome, controlling for observables x) and the selection effect (i.e., the effect of u on preference for comfort, controlling for observables x).

Table A-6: Sensitivity analysis

	Fraction $u = 1$ by treatment/outcome				Outcome effect	Selection effect	Report restricting consumption	SE
	P_{11}	P_{10}	P_{01}	P_{00}				
temperature								
No confounder	0	0	0	0	-	-		
Neutral confounder	0.50	0.50	0.50	0.50	1.010	1.004	-0,486	0.004***
<i>Confounder like:</i>								
Percentile 2	0.18	0.22	0.18	0.17	1.068	1.287	-0,488	0.006***
Percentile 1	0.35	0.25	0.15	0.15	1.033	2.117	-0,493	0.013**

Homeowner	0.58	0.65	0.78	0.78	0.989	0.497	-0,492	0.015**
Cooling system	0.13	0.03	0.10	0.07	1.497	0.591	-0,482	0.006***
Possible to adjust the heating	0.82	0.87	0.75	0.83	0.613	1.496	-0,477	0.008***
House	0.68	0.70	0.67	0.77	0.596	0.807	-0,494	0.008***

*** Significant at 1%. ** significant at 5%. * significant at 10%, ns not significant

The first four columns give the four probabilities, s_{ij} , which define the distribution of the unobservable components by restricting heating consumption and outcome. Column 5 gives the outcome effect. Similarly, column 6 presents the selection effect. The two last columns provide the effect and the standard error of restricting heating consumption, controlling for the observable x and the unobservable U . We present the results of a sensitivity analysis for households that restrict their heating consumption when the distribution is comparable for income, ownership, having a cooling system, and the ability to adjust the heating.

For example, P11 equals 0.18, i.e. 18% of households who restrict their heating consumption by 0.488 Celsius belong to percentile 1. The effect of restricting heating consumption is just slightly higher than in the situation without a confounder (-0.488 vs. -0.486), but the effect is still negative and significant and almost the same.

Overall, the results of the sensitivity analysis for temperature indicate that the simulated matching estimators do not differ from the baseline estimates and remain statistically positive and significant, whatever the type of distribution chosen for U . All these simulations support the robustness of the matching estimates, whatever the distribution chosen for U .

B. Results

Table B-1: Profile of fuel-poor households according to definitions

	Measure of fuel poverty according to...												Whole sample	
	10%			AFCP			LIHC			FPI			Mean	Std. Dev.
	Mean	Std. Dev.	<i>t</i> test ^o	Mean	Std. Dev.	<i>t</i> test ^o	Mean	Std. Dev.	<i>t</i> test	Mean	Std. Dev.	<i>t</i> test [‡]		
Percentile 1	0.520	0.501	***	0.503	0.501	***	0.740	0.440	***	0.136	0.040	***	0.193	0.395
Percentile 2	0.281	0.451	***	0.309	0.463	***	0.226	0.420	ns	0.118	0.028	***	0.190	0.393
Percentile 5	0.104	0.307	***	0.131	0.338	***	0.030	0.171	***	0.110	0.027	**	0.186	0.390
Percentile 4	0.081	0.274	***	0.057	0.232	***	0.004	0.062	***	0.097	0.022	***	0.214	0.410
Percentile 5	0.012	0.111	***	0.000	0.000	***	0.000	0.000	***	0.081	0.021	***	0.216	0.412
Homeowner	0.642	0.481	***	0.491	0.501	***	0.402	0.492	***	0.104	0.032	***	0.695	0.461
Possible to adjust the heating	0.837	0.370	ns	0.735	0.442	***	0.676	0.469	***	0.109	0.032	ns	0.805	0.396
Preference for comfort for heating	0.446	0.498	ns	0.510	0.501	***	0.543	0.500	***	0.114	0.035	***	0.412	0.492
Climate zone 1 (coldest – North)	0.680	0.468	ns	0.582	0.494	ns	0.695	0.462	***	0.108	0.035	ns	0.583	0.493
Climate zone 2	0.272	0.446	ns	0.337	0.473	ns	0.220	0.415	***	0.110	0.032	**	0.328	0.470
Climate zone 3 (warmest – South)	0.049	0.216	ns	0.081	0.273	ns	0.085	0.280	ns	0.099	0.031	***	0.089	0.285
Energy consumption per m2	278.3	141.4	***	162.028	119.633	ns	203.7	126.5	***				164.1	136.8
Construction period before 1919	0.298	0.459	***	0.227	0.420	***	0.170	0.377	ns	0.118	0.037	***	0.164	0.370
Construction period between 1919 and 1945	0.152	0.360	***	0.113	0.317	ns	0.096	0.296	ns	0.115	0.036	***	0.096	0.294
Construction period between 1946 and 1970	0.252	0.435	ns	0.252	0.435	**	0.279	0.450	***	0.107	0.035	ns	0.212	0.409
Construction period between 1971 and 2005	0.239	0.428	**	0.252	0.435	**	0.299	0.459	ns	0.102	0.031	***	0.309	0.462
Construction period between 1946 and 1970	0.040	0.198	***	0.109	0.312	***	0.103	0.305	**	0.102	0.031	***	0.157	0.364
Construction period after 2005	0.018	0.134	**	0.047	0.212	ns	0.051	0.221	ns	0.106	0.030	ns	0.063	0.243
House	0.794	0.406	ns	0.496	0.501	***	0.406	0.493	***	0.112	0.032	***	0.666	0.472
Temperature	19.828	1.525	ns	19.796	1.786	*	19.917	2.176	ns				19.982	1.573
Report restricting heating consumption	0.364	0.482	ns	0.360	0.481	***	0.420	0.495	***	0.120	0.036	***	0.232	0.422
% cutting or strongly restricting heating	0.636	0.482	ns	0.640	0.481	***	0.580	0.495	***	0.104	0.032	***	0.769	0.422
% limiting the heating time in the day	0.080	0.272	*	0.094	0.292	***	0.113	0.318	***	0.120	0.033	***	0.051	0.220
% limiting the number of heating weeks in the year	0.043	0.204	*	0.075	0.264	***	0.088	0.285	**	0.120	0.037	***	0.039	0.194
% not heating some rooms	0.010	0.101	*	0.033	0.178	***	0.045	0.208	*	0.136	0.047	***	0.014	0.118
% using auxiliary heater instead of main heater	0.165	0.372	***	0.109	0.312	***	0.113	0.318	**	0.118	0.036	***	0.077	0.267
% others	0.036	0.188	ns	0.024	0.155	ns	0.024	0.152	ns	0.125	0.029	***	0.028	0.165
Cold discomfort	0.245	0.431	***	0.316	0.466	***	0.403	0.492	***	0.116	0.038	***	0.192	0.394
Cold discomfort Insufficient heating installation	0.033	0.180	ns	0.112	0.317	ns	0.152	0.362	ns	0.100	0.038	***	0.119	0.324

Cold discomfort Installation failure	0.135	0.346	ns	0.156	0.365	ns	0.129	0.338	ns	0.116	0.116	ns	0.128	0.334
Cold discomfort Financial reasons (privation)	0.299	0.463	***	0.154	0.363	**	0.151	0.361	ns	0.128	0.033	***	0.126	0.332
Cold discomfort Bad insulation	0.216	0.416	ns	0.339	0.476	ns	0.362	0.484	ns	0.124	0.040	***	0.306	0.461
Cold discomfort Unpaid power provider	0.000	0.000	ns	0.000	0.000	ns	0.000	0.000	ns	–			0.002	0.048
Wrong setting	0.016	0.128	ns	0.044	0.206	ns	0.048	0.216	ns	0.081	0.031	***	0.043	0.204
Harsh winter	0.182	0.390	ns	0.119	0.326	**	0.096	0.297	ns	0.117	0.037	ns	0.178	0.383

t* test between fuel poor and not fuel poor. * Significant at 1%. ** significant at 5%. * significant at 10%, ns not significant ‡differences of means values of FPI according to household characteristics. For example, the value of FPI is statistically different for households belonging to the first decile relative to others.