Measuring energy poverty: uncovering the multiple dimensions of energy poverty

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Abstract

Indicators are essential tools for monitoring the evolution of energy poverty and targeting support policies. If the multidimensional nature of energy poverty is widely recognised, policy makers generally rely on a budgetary approach. This choice is debated and has strong political implications. This paper adopts a broader definition of energy poverty based on the capability approach and aims to operationalize it. It develops a multidimensional energy poverty index (MEPI), which combines the multiple factors that disadvantage households in terms of energy. Contrary to existing indicators, this new index captures the energy poverty experienced by households in its different dimensions, from financial burden to material deprivation and behavioural restriction. Two indices are designed: one for housing and one for mobility. Results suggest budgetary indicators could lead to important inclusion and exclusion errors as well as distort the evaluation of support policies. Quantification in the French context brings new insights on the targeting of policy responses and emphasizes the need to address the non-monetary dimensions of energy poverty.

Keywords: Energy poverty; Multidimensional measurement; Energy services; Inclusion and exclusion errors; Housing and Transport

JEL Classification: I32, I38, Q4, Q56

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1. Introduction

Energy provides many essential services in daily life, such as heating, traveling, lighting or refrigerating food. Energy poverty refers to households who face difficulties to satisfy these essential energy services. Distinct from poverty, energy poverty is associated with harmful consequences for health, well-being and social inclusion (Healy, 2003; Liddell and Morris, 2010; Braubach, 2011; Lucas et al., 2016). As such, it has an indirect effect on various policy areas - health, environment, productivity - and reducing energy poverty could bring multiple benefits. Moreover, some environmental policies, because they raise the price of energy, are likely to weaken part of the population (Parry et al., 2005; Fullerton, 2008). As such, energy poverty cannot be separated from ecological issues. The fight against energy poverty has recently been identified as one of the main priorities by policy-makers in Europe (Clean Energy for All Europeans Package in 2016) and in the world (Sustainable Development Goals for 2015-2030). Thus, ensuring a fair ecological transition emphasizes the need to implement policies to support the energy poor.

The design of appropriate indicators of energy poverty is therefore needed to monitor the phenomenon and guide the targeting of policy responses. Yet, existing indicators of energy poverty raise some concerns (Thomson et al., 2017). The extent of the phenomenon and the populations identified are not the same from one indicator to another (Legendre and Ricci, 2015; Imbert et al., 2016; Waddams Price et al., 2012). These differences are problematic for public actors. If inadequately targeted, energy poverty policies may miss their intended purpose.

More importantly, if there is a large consensus on the multidimensional nature of energy poverty, policy makers generally rely on a budgetary approach. Although they provide some essential information, they capture only a partial picture of the energy poverty (Thomson et al., 2017). Prior work has mostly consisted in comparing advantages and drawbacks among different budgetary measures (Moore, 2012; Hills, 2011, 2012). This does not tell us to what extent budgetary indicators succeed or not to capture the non-budgetary dimensions of energy poverty. Consequently there is a large contrast between simplistic indicators and a broader but not yet operational challenge.

Not much has been done to include the various dimensions of energy poverty into a single index (Tirado Herrero, 2017). If a few authors have proposed multidimensional measures, however they did it seperately, without comparing their results with budgetary measures (Healy and Clinch, 2002; Nussbaumer et al., 2012; Thomson and Snell, 2013; Okushima, 2017; Charlier and Legendre, 2016). One can question whether a budgetary approach constitutes a good proxy for quantifying energy poverty. Because it is much simpler to implement - it is less data intensive - it could be the prefered option for policy makers. However, if it leads to important inclusion and exclusion errors, then it could misguide the targeting of support policy. Similarly if a budgetary approach fails to cover some dimensions of energy poverty, then it could hide evolution in those dimensions and distort the evaluation of related support policies.

This paper aims at building a new measurement able to account for a more comprehensive vision of energy poverty. Drawing on the work of Day et al. (2016), I interpret energy poverty in the capability framework as *"the inability to achieve essential capabilities resulting directly or indirectly from insufficient access to affordable, reliable and safe energy services, taking into account reasonable and available alternative means of* *achieving these capabilities"*. To operationalise this definition, I combine the different dimensions of energy poverty within a single index - the multidimensional energy poverty index (MEPI) - using the double threshold methodology (Alkire and Foster, 2011). It allows to capture the different factors that disadvantage households in terms of energy, from financial burden to material deprivation and behavioural restriction. Two indices are designed: one for housing and one for mobility.

I then show how these new indices, because they address households' cumulative disadvantages, can help limit the inclusion and exclusion errors blamed on budgetary approaches. Concretely, the more a household is identified in different factors, the more problematic its situation is likely to be. Such an approach offers a more comprehensive and robust picture of energy poverty compared to existing indicators. Ultimately, the aim of this study is not so much to construct a perfect index, but rather to show that measuring energy poverty as a multidimensional concept has strong political implications in terms of charaterizing the phenomenon and targeting support policies.

Implementation and comparison with existing indicators is illustrated with an application to the French case study based on the survey Phebus 2012.

The rest of this paper is organised as follows. The second section motivates the definition of energy poverty retained in this paper and reviews existing attempts to measure energy poverty as a multidimensional concept. The third section describes the methodology used to build the Multidimensional Energy Poverty Index (MEPI). The survey data and the construction of the index adopted in housing and transport in the French case study are presented. The fourth section describes the main results on the incidence of energy poverty, the comparison with existing indicators and the composition of energy poverty. The fifth section discusses policy implications and the applicability of the MEPI, before concluding.

2. Background

2.1. Conceptualising energy poverty

Definitions of energy poverty vary widely in the literature. Part of the difficulty in agreeing on a satisfactory definition lies in the fact that energy is not an end in itself, but a vector to fulfill a set of energy services. It is also difficult to specify a simple criterion for determining whether a level of energy services is acceptable or not. This section revisits the concept of energy poverty and motivates the definition retained in this paper.

The terminology of energy poverty, or fuel poverty, was born in the United Kingdom in the 1970s following an increase in winter mortality as a result of rising energy prices. In the academic literature, the term was first used by Bradshaw and Hutton (1983) to refer to households who have difficulty in adequately heating their homes. In 1991, Boardman (1991) proposed a more operational definition, which was adopted by the UK government. These are households that spend more than 10% of their income on energy. This definition is extended to include energy services other than heating: lighting, cooking, and services provided by other electrical equipment. It has since become a reference and is widely used in other developed countries. In 2013, the UK government reviewed its definition and (Hills, 2011, 2012): a household is said to be energy poor if he needs to spend more than the national median and if he had a residual income below the income poverty line, if it spent that amount. This indicator, called Low Income High Costs (LIHC), focuses on the least efficient dwellings occupied by low-income households. These two definitions - energy expenditure ratio and LIHC - relate to budgetary indicators. They specify some statistical criteria on the energy spending to identify the energy poor. As such, they implicitly assume the energy spending can reveal the various difficulties households meet to fulfil essential energy services, a position that is not widely accepted (Tirado Herrero, 2017; Thomson et al., 2017). If such definitions can be valued for their operability, however they may misrepresent the phenomenon and misguide policy makers.

The situations faced by energy poor are diverse, which calls for acknowledging the multidimensional nature of energy poverty in its the definition and measurement (Tirado Herrero, 2017). In this perspective, the work of Day et al. (2016) makes an important move in that direction. The authors conceptualise energy uses in the capability space of Amartya Sen[1] (Sen, 1992). They highlight capabilities can refer to physical health, well-being, quality of life, social inclusion, living conditions and so on. These so-called basic capabilities then refer to a number of secondary capabilities - washing one's clothes, preparing meals, going to the doctor's office - which in turn refer to energy services - lighting, heating one's home, refrigerating and cooking food, moving around - which in the end refer to the supply of energy - electricity, natural gas, petrol, diesel (see figure 1). Based on that approach, they define energy poverty as *"the inability to achieve essential capabilities resulting directly or indirectly from insufficient access to affordable, reliable and safe energy services, taking into account reasonable and available alternative means of achieving these capabilities"*. Such definition makes it possible to recognise the diversity of the impacts of energy poverty and it offers new scope for action, which is particularly useful in the current context of fighting climate change and reducing energy consumption[2].

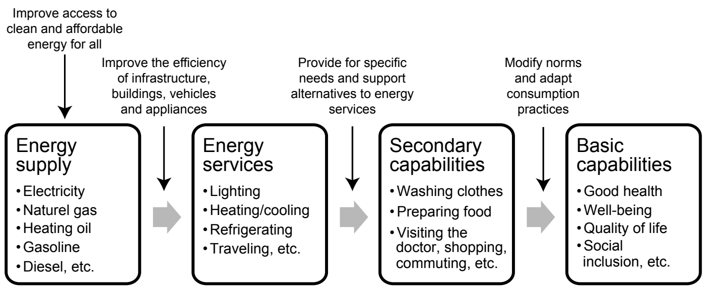

Figure 1: Conceptualising energy uses in the capability space (adapted from Day et al. (2016))

This paper relies on the work of Day et al. (2016) to quantify energy poverty as

[1]The capability approach has contributed to influencing the way in which well-being is conceived and measured at the international level (Stiglitz et al., 2009). It has supported the creation of multidimensional indicators, which provide complementary information to monetary approaches, including the HDI and the MPI. Such an approach distinguishes between what individuals are free to do (capabilities) and what they do (functionnings).

[2]Policy responses can thus be positioned at different levels: improve access to clean and affordable energy for all; improve the efficiency of infrastructure, buildings, vehicles and appliances; ensure that the specific needs of certain vulnerable populations are met and provide alternatives to energy services; as well as modify norms and adapt consumption practices.

a multidimensional concept. The approach is broadened to include transport energy in addition to housing energy. Indeed, an increase in fuel prices could weaken part of the population in a context where many households have no adequate alternative to car usage in their daily life: to commute, to shop, to go to the doctor, to visit family and friends, etc. (Berry et al., 2016; Mattioli et al., 2017). Another motivation for evaluating energy poverty in both sectors is to analyse whether households affected are the same or differ. They may suffer from a double penalty if they cumulate poor housing characteristics and poor mobility conditions. This study will seek to determine to which extent households affected by energy poverty in housing are the same or differ from those affected in mobility.

2.2. Measuring energy poverty as a multidimensional concept

Questions of multidimensional measures have been studied extensively in other fields, especially poverty (Bourguignon and Chakravarty, 2003; Atkinson, 2003; Alkire and Foster, 2011). It resulted in the production of conceptual frameworks and multidimensional indices. The double threshold methodology is one of the methods that have been applied to evaluate multidimensional poverty[3], based on the capability approach (Alkire and Foster, 2011). In such approach, poverty can be quantified at each household level using available information. This method could meet the urgent need for better evaluating multidimensional energy poverty.

Table 1: Review of existing multidimensional measures of energy poverty

Study	**Number of indicators**	**Identified as energy poor if deprived in...**	**Level of energy poverty**	**Country covered**
Healy et al. 2002	6 indicators (3 objective + 3 subjective)	NA	Weighted arithmetic mean of each indicator	14 European countries
Thomson et al. 2013	3 indicators (1 objective + 2 subjective)	NA	Weighted arithmetic mean of each indicator	25 European countries
Charlier et al. 2016	3 indicators (2 budgetary + 1 objective)	NA	Weighted geometric mean of each indicator	France
Okushima 2017	3 indicators (2 budgetary + 1 objective)	All 3 indicators (intersection approach)	Share of households identified energy poor	Japan
Nussbaumer et al., 2012	6 indicators (all objective)	30% of indicators	Share of households identified energy poor	29 African countries

Yet few studies have addressed the multidimensional nature of energy poverty so far. Table 1 summarizes existing attempts and their main characteristics. The five studies rely on different methodologies to quantify energy poverty. Three studies estimate energy poverty as the weighted arithmetic or geometric mean of different indicators (Healy and Clinch, 2002; Thomson and Snell, 2013; Charlier and Legendre, 2016). However such methods are limited in its applicability. They do not allow to identify who is energy poor

[3]It has been intensively used to evaluate poverty in developing countries, and more recently in some developed countries, such as in Europe.

or not at the end of the process. The final measure does not represent actual incidence, but an average incidence of different indicators. Though one knows if a household is identified or not by an individual indicator, it does not tell us which households are identified energy poor under the final aggregated measure. Thus the interpretation is not intuitive and it brings only limited information on the design and targeting of support policies. The two last studies overcome this drawback by relying on an identification and aggregation method (Nussbaumer et al., 2012; Okushima, 2017). They both apply the double threshold methodology. Yet these two studies are limited in their scope: one study relies essentially on budgetary indicators - for which critics were stressed above - while the other is related to developing countries - where manifestations of energy poverty are of different nature. The five studies, and their detailed set of indicators, are further described in Appendix A.

In the following, I propose to design a single index, which has the synthetic aspect of unidimensional indicators, but which accounts for the multiple dimensions of energy poverty. Therefore it is closer to the actual experience of households. This index focuses on the combination of factors that put households at a disadvantage when it comes to energy, in the context of developed countries. Two indices are evaluated: one for housing and one for transport. The two sectors are analysed separately because difficulties in one sector do not compensate with difficulties in the other sector.

3. Methodology

This study draws on the literature to measure multidimensional poverty and applies it to data on energy services. The proposed methodology is common to many measures, which are divided into two steps: an identification step followed by an aggregation step (Sen, 1976). The identification step defines thresholds for distinguishing between energy poor and non energy poor households. The aggregation step brings together the characteristics of energy poor within a new global index of multidimensional energy poverty[4].

For the identification step, energy poor are identified according to the double threshold method developed by Alkire and Foster (Alkire and Foster, 2011). Such method is a recent contribution which brings many useful properties (see Appendix B). The first threshold is specific to each indicator. As such, a threshold is set for each indicator individually and identifies whether or not a household is disadvantaged in this indicator. The second threshold defines how disadvantaged a household must be in order to be considered energy poor. Different weights can be applied to the indicators. If all indicators have an equal weight, the second threshold is simply the number of indicators in which a household must be disadvantaged to be considered energy poor. This equal weight approach, also known as the counting approach, is commonly used in social policies[5].

[4]These two steps also apply to one-dimensional measurements. For example, in the literature, the step of identifying energy poor households is usually solved by using the energy expenditure ratio method, which requires specifying a maximum ratio above which the energy expenditure is considered disproportionate compared to the household income. This maximum acceptable ratio is called the energy poverty threshold. A person is said to be in energy poverty if its ratio is higher than the threshold of energy poverty. On the aggregation step, the most widely used measure is the incidence, i. e. the rate of energy poor. This corresponds to the number of households with an energy expenditure ratio above the energy poverty threshold divided by the total number of households in the population.

[5]For example, the main indicator for monitoring the poverty reduction objective of the Europe 2020

Once households in energy poverty have been identified, it is then necessary to summarise the information within a single index, which corresponds to the aggregation step. The headcount ratio H is used to measure the incidence of energy poverty, that is to say the proportion of households that are identified as multidimensional energy poor in total population.

$$H = \frac{q}{n} \tag{1}$$

With q the number of energy poor households ($c_i k$) and n the total number of households in the population. The headcount ratio belongs to the Foster-Greer-Thorbecke (FGT) measures and is widely used in income poverty measurement (Foster et al., 1984). The MEPI relates to the headcount ratio H in this study. A mathematical formalization of the methodology is described in Appendix B.

3.1. Data

In this paper, quantification is done in the French context and uses the recent survey Phebus. Phebus was carried out in 2013 for the statistical service of the French Ministry of Ecology (SOeS). It aims to inform public policies on household energy consumption and the energy performance of the housing stock. It is a cross-sectional survey representative of the French residential dwelling sector. A sample of 5405 households - living in dwellings statistically selected to represent about 27 million housing-units - was interviewed. It contains two parts. The first part is a face-to-face interview with the households which contains detailed information on their socio-demographic characteristics and their energy uses, such as energy consumption, heating systems, housing characteristics, electric appliances, behaviours and preferences, as well as some questions about mobility practices. The second part, which concerns only a subsample of 2356 dwellings, consists in an energy performance diagnosis of the dwelling which was carried out by certified professionals. For those dwellings, the survey contains both observed and theoretical energy consumption.

The choice of Phebus takes into account some limitations, yet this database brings many advantages for the purpose of the study - to develop a multidimensional measure of energy poverty in housing and transport. The data are recent and the information is not only budgetary. It is also the first database containing detailed information on energy consumption and practices in both housing and transport at the household level - without matching different databases. No other European countries have such detailed database to my knowledge. However, this choice introduces two main limitations. The sample is relatively small in Phebus compared to other national surveys, which limits the scope for detailed study of some minority household categories. Moreover, the data are only available for one year so far, so that this survey does not allow to study the evolution over time. In the following, one has to keep in mind the design of the index remains constrained by data availability. Though it is the most detailed database at the time of the study, some factors that disadvantage households in terms of energy use are not available and therefore could not be evaluated.

Strategy identifies households "at risk of poverty or social exclusion" if they are disadvantaged in at least one of the following three dimensions: income poverty, severe material deprivation and unemployment.

3.2. The unit of analysis

The unit of analysis corresponds to households. A first reason is that data is available at the household level in the Phebus survey. More importantly, this choice is motivated by the objective pursued. All members of a household share the same housing and income conditions. Thus they are all affected by cold temperatures or disproportionate energy expenditure. On the transport side, this choice is more questionable. Mobility is above all individual - the motives and destinations differ between individuals in the same household. In Phebus, some of the questions related to mobility are asked to individuals. A household is said to be disadvantaged if at least one of its members is identified as disadvantaged. Other questions are asked directly to the household - so the answer concerns all members directly.

3.3. Choosing the dimensions

Two indices are designed: one for housing and one for transport. For each sector, five dimensions of energy poverty are considered respectively. The two indices are designed according to the same logic: one dimension directly concerns an energy service, two dimensions concern non-monetary resources and two dimensions concern monetary resources (see table 2). Resources, whether monetary or non-monetary, are used as proxies for evaluating a range of energy services: heating, washing, refrigerating, cooking, moving, etc. If the impacts on health are not a distinct dimension, these impacts are indirectly captured through some factors included in the indices.

Table 2: The five dimensions included in the MEPI for housing and transport

Dimension	**Nature**
Housing/Mobility conditions	Non-monetary resource
Equipment	
Restriction	Energy service
Energy spending	Monetary resource
Standard of living	

3.4. Choosing the indicators and their identification thresholds

The multidimensional nature of energy poverty should be reflected in the choice of indicators. In this paper, the selection of the indicators is based on a review of academic literature and reports, as well as on the availability of data - a feasibility criterion rather than a selection criterion. Similarly, the choice of thresholds for each indicator is based as much as possible on national and international standards and literature. The indicators and thresholds used in the MEPI are presented in figure 2 for housing and figure 3 for transport.

3.4.1. Housing indicators

Adequate heating is an essential service. Studies show that being cold at home has direct effects on health (Liddell and Morris, 2010) (Host et al., 2015) and is a major cause of winter excess mortality (Healy, 2003) (Liddell et al., 2016). Two indicators are included to capture restriction with heating. The first is the temperature in the housing[6]. In France, ADEME recommends heating to 19°C for a comfortable situation. Following recommendations from the World Health Oragnisation, the minimum acceptable temperature is adjusted to 20°C for certain vulnerable populations - elderly people, young children and disabled (Braubach, 2011). The second indicator is declarative. It identifies housholds reporting feeling cold because of the five following reasons: insufficient heating system, failure of the heating system, restriction of heating due to cost, poor insulation, and power disconnection due to unpaid bills[7].

An excessive energy spending can impact household budgets, at the risk of unpaid bills or restrictions on other essential expenses, such as food (Anderson et al., 2012) (Beatty et al., 2014) (Bhattacharya et al., 2003). The energy expenditure ratio is the most widely used indicator for measuring energy poverty in developed countries. The threshold is set at twice the national median.

The dwelling energy performance is one of the main determinants of energy poverty (EPEE, 2006) (Boardman, 2013). A well-insulated dwelling requires less energy to achieve the same level of comfort - even if this gain can be reduced by rebound effect (Greening et al., 2000) (Sorrell et al., 2009)[8]. It also limits risks of poor indoor air quality through the accumulation of pollutants, dust mites and excess moisture, which has direct effects on health (Wilkinson et al., 2009) (Maidment et al., 2014) (Bonnefoy, 2007). This indicator identifies the least energy efficient dwelling, whose energy consumption is over 330 kWh/m2/year.

The services provided by household equipment have been included to capture elements related to other energy uses - than heating - in the dwelling that are generally absent from energy poverty measures. Yet they constitute basic necessities for achieving a decent standard of living (Day et al., 2016). Moreover the oldest and least efficient equipment is often owned by low-income or vulnerable households, contributing to energy poverty by putting pressure on their energy bills (Simcock et al., 2016) (Healy and Clinch, 2002). Three indicators are included to capture equipment. The first indicator is on the energy efficiency of six appliances: washing machine, dryer, dishwasher, refrigerator, combined refrigerator and freezer. It identifies appliances with energy label A or below bought in the last 5 years[9]. The second indicator is on the presence of a temperature control system in the dwelling. Indeed, the ability to regulate temperature is a prerequisite for controlling heating spending. The third indicator identifies poor types of heating.

[6] The temperature reported in the Phebus survey refers to the temperature of the dwelling when the household is present on an ordinary day. Such an indicator, which is theoretically simple, raises a number of technical problems regarding the reliability of housing temperature data (Milne and Boardman, 2000) and in identifying other specific situations, such as people suffering from chronic pathologies for which the comfort temperature differs or the ability to heat during an episode of extreme cold.

[7] However, it does not identify households reporting feeling cold because of incorrect adjustment, delayed start-up of the system, particularly severe winter or other reasons.

[8] For example, Milne and Boardman (2000) found that among households that do not heat up enough, about 30% of the efficiency gain is used to increase heating temperature.

[9] The objective is to make the most efficient equipment available to all households at the time of purchase, and not to push ahead with the early replacement of existing equipment that has not yet reached the end of its useful life. Furthermore, focusing on recent appliances also limits the stock effect that would hide the evolution of the indicator and the progress made in the new devices acquired, on which policies can act.

It identifies households using a chimney, heating cooker or mobile appliances - electric or other - as their main heating system or as a regular backup[10] as well as households with no means of heating. The frequent use of an open chimney is a source of indoor air pollution, which has harmful health effects (Burr, 1999; Jones, 1999); and heating mainly with mobile appliances is taken as a proxy for the deficiency of a suitable heating system in the dwelling.

Finally, the standard of living - disposable income per unit of consumption - identifies the most financially constrained households. Those households are also less able to invest in energy efficient equipment and dwelling renovation.

	Dimension	Indicator	Disadvantaged if...	Weight
Housing	Restriction	Indoor temperature	<19°C Or < 20°C if [age≥65, age≤7 or disable]	1/10
		Felt cold	Yes, if among 5 reasons*	1/10
	Housing conditions	Dwelling energy performance	>330 kWh/M2/year (Energy certificate if available, or actual consumption)	1/5
	Equipment	Energy efficiency of appliances	>1 appliance with energy label A, B, C or more, less than 5 years old, among: washing machine, dryer, dishwasher, refrigerator, combined refrigerator and freezer.	1/15
		Presence of a temperature control system	No	1/15
		Type of heating	Used as main or regular backup heater: chimney OR heating cooker OR mobile appliances OR no means of heating.	1/15
	Energy spending	Energy expenditure ratio	> 2x national median (=0,09%)	1/5
	Standard of living	Disposable income per UC	< Decile 4	1/5

* The five reasons for feeling cold are: 1/ Insufficient heating system, 2/ Failure of the heating system, 3/ Restriction of heating due to cost, 4/ Poor insulation, 5/ Power disconnection due to unpaid bills

Figure 2: Description of MEPI in housing

3.4.2. Transport indicators

Mobility is a necessary condition for social inclusion (Lucas, 2012), so that "being mobile" has become an injunction in our modern societies (Bacqué and Fol, 2007). Two indicators are included to capture restriction in mobility. Declared restriction of car use directly informs about the ability to satisfy one's motorised mobility. Households are identified if this restriction results in reduced distance travelled, indicating a probable inability to meet a travel need[11]. However, not restricting mobility does not systematically translates

[10] When used as an exceptional backup, they are not identified as some households may enjoy using their chimney in the winter or their mobile heating in very cold weather.

[11] When the restriction leads to the use of alternatives to the car - public transport, car-sharing, use of a single vehicle or other - then the existence of an alternative to the use of the vehicle is proven and the household is not considered disadvantaged in this indicator - its need for mobility is a priori fulfilled.

into a satisfied mobility. A declarative variable in which households state if they have difficulties in meeting fuel costs is added as a proxy to identify these other situations.

An excessive spending can impact household budgets, at the risk of deprivation of other essential expenditure (Gicheva et al., 2010) or of increasing debts (Walks, 2017). The energy expenditure ratio is the most widely used indicator for measuring energy poverty in mobility (Mattioli et al., 2017). The threshold is set at twice the national median.

The energy efficiency of vehicles is one of the main drivers for reducing fuel consumption - though this gain can be reduced by rebound effect. Yet the most efficient vehicles are not always accessible to low income households, who mainly buy on the second-hand market. This indicator identifies the least efficent vehicles. In the absence of more accurate data, it identifies vehicles whose fiscal power is strictly over 5.

Accessibility to services is crucial for ensuring social and territorial cohesion. Cars being only one mean to meet mobility needs, it is also possible to act on other factors, such as the demand for mobility, the quality and cost of other means of transport, terrotorial accessibility and residential location. The first indicator informs about the existence of at least one public transport stop near the dwelling. If the existence of a stop does not guarantee the ability to access a range of services in daily life, the absence of a stop is clearly disadvantageous for some households (Orfeuil, 2004). One can think of the elderly, households whose income does not allow regular car use, people with reduced mobility or people who do not have a driving licence. This variable is a proxy to inform about the dependence on car use. A second indicator is declarative and informs about the existence of an alternative to access essential services. It identifies households with at least one member declaring that the use of a vehicle as a driver is unavoidable for commuting. Ideally, it would have been desirable to consider a wider range of essential services (health, shopping, childhood care, etc.), but data on other motives are not available in the survey. Finally, it would have been desirable to add a variable measuring the distance (or time of access) to daily life services in order to inform on the degree of accessibility of the territory, as well as on the adequacy of the residential location with households's needs, but these data are not available in the survey.

Finally, the standard of living - disposable income per unit of consumption - identifies the most financially constrained households. Those households are also less able to invest in energy efficient cars or to choose their residential location.

Tables 3 and 4 report some descriptive statistics on the quantitative and qualitative variables used to quantify multidimensional energy poverty.

	Dimension	Indicator	Disadvantaged if…	Weight
Transport	Restriction	Restriction of car use (among households using cars)	Yes, if results in a reduction in travelled distance	1/10
		Difficulty in meeting fuel costs (among households using cars)	Yes	1/10
	Mobility conditions	Alternative to car (among households using cars)	No, for commuting	1/10
		Access to public transport	No stop near the dwelling (<600m or <10 min by foot).	1/10
	Equipment	Car energy efficiency (among households using cars)	Fiscal power >5	1/5
	Energy spending	Fuel expenditure ratio (among households using cars)	> 2x national median (=0,08%)	1/5
	Standard of living	Disposable income per UC	< Decile 4	1/5

Figure 3: Description of MEPI in transport

Variables in housing	**Mean**	**S.E.**	**p25**	**p50**	**p75**
Disposable income (€/year)	34 479.77	292.17	19 989.00	29 707.00	43 253.00
Domestic energy spending (€/year)	1 563.43	12.72	940.16	1 397.73	1 954.11
Domestic energy expenditure ratio (%)	5.62	0.06	3	4.49	6.97
Dwelling energy perfomance (kWh/m2)	288.66	3.25	180.99	259.52	352.69
Actual energy consumption per m2 (kWh/m2)	182.38	2.49	82.98	143.48	230.17
Indoor temperature (°C)	20.02	0.02	19	20	21
Variables in transport					
Fuel spending* (€/year)	1 807.92	22.94	780.22	1 439.67	2 400.37
Fuel expenditure ratio* (%)	5.65	0.08	2.5	4.15	7.13

* Among households using cars

Table 3: List and description of quantitative variables used for the MEPI.

Variables in housing	**Categories**	**Frequency**
Feeling cold	Yes	20.58
	No	79.42
Reason for feeling cold	Insufficient heating system	2.52
	Failure of heating system	2.45
	Restriction of heating due to cost	2.51
	Poor insulation	6.32
	Power disconnection due to unpaid bills	0.11
	Incorrect adjustment or delayed start-up	1.31
	Particularly severe winter	3.62
	Other reasons	1.67
	NA	79.49
Number of inefficient appliances	0	78.37
	1	13.95
	2	5.46
	3+	2.21
Temperature control system	Yes	74.63
	No	25.37
Heating cooker	Main heater	66.20
	Regular backup	26.43
	Exceptional backup	9.18
	Non used	2.29
Chimney	Main heater	30.22
	Regular backup	26.43
	Exceptional backup	34.71
	Non used	8.64
Mobile appliances (non electric)	Main heater	29.74
	Regular backup	25.07
	Exceptional backup	41.49
	Non used	3.70
Mobile appliances (electric)	Main heater	18.92
	Regular heater	22.59
	Exceptional heater	53.99
	Non used	4.49
Variables in transport	**Categories**	**Frequency**
Difficulty in meeting fuel costs	Yes	14.68
	No	85.32
Restriction in car use	Yes	43.78
	No	56.22
Reduction in travelled distance	Yes	18.06
	No	81.94
No alternative to car	0 member	66.99
	1 member	22.81
	2+ members	10.20
Access to public transport	Yes	74.70
	No	25.30
Car energy efficiency	Fiscal power 5	82.18
	Fiscal power >5	17.82

Table 4: List and description of qualitative variables used for the MEPI.

3.5. Choosing the weights

Weights are assigned at two levels: between dimensions (for example, the relative weight between standard of living and restriction) and within dimensions (between indicators of the same dimension). The choice of dimensions, thresholds and weights between dimensions are interconnected. In this paper, the indices for housing and transport are both constructed in such a way that the dimensions have an equal relative weight[12]. Similarly, the two indices apply the same weight to each indicator within the dimensions. It is difficult to judge the relative importance of indicators within the same dimension. For example, in the case of restriction indicators, it could be argued that a household suffering from cold is the most crucial aspect; however, an adequate indoor temperature of the dwelling is also essential for maintaining good physical and mental health. These two indicators reflect major deprivations and it is not clear which one is more important. In the case of services provided by household equipment, the energy efficiency of appliances, the type of heating and the presence of a temperature control system are three key aspects for controlling one's energy consumption, so assigning relative importance to them is not obvious.

3.6. Choosing the threshold for multidimensional energy poverty

The next step is to define the threshold for identifying the multidimensionally energy poor households from households that are not. Identification in the housing and the transport is done separetely. In each sector, each household cumulates a number of disadvantages (i.e. indicators in which it is disadvantaged). The threshold represents the minimum number of weighted disadvantages that a household must cumulate to be considered multidimensionally energy poor. A first approach is to consider a household as energy poor if it is disadvantaged in at least one indicator - the union approach. But having one disadvantage does not necessarily represent energy poverty. At the opposite, another approach is to consider a household as energy poor if it is disadvantaged in all indicators - the intersection approach. This approach is very demanding. It excludes households that cumulate multiple disadvantages, but not all, and that would deserve to be considered energy poor. The MEPI allows for an intermediate approach. A household is energy poor if it is disadvantaged in several indicators at the same time. The choice of the threshold will depend on the intensity of the situations one wishes to identify. The next section looks at how many households are identified energy poor in housing and transport respectively according to the threshold.

4. Results

4.1. Incidence et intensity of energy poverty

Figure 4 shows the incidence (H) and intensity (A) of multidimensional energy poverty as a function of the threshold. I find that the incidence of energy poverty in housing

[12] This choice follows the recommendation made by Atkinson et al. (2002) in their work on social indicators in Europe: *"the interpretation of the set of indicators is greatly eased where the individual components have degrees of importance that, while not necessarily exactly equal, are not grossly different".*

and transport is of the same magnitude for all thresholds. Incidence curves in transport (dark blue) and housing (dark purple) are very close to each other and regularly intersect according to the threshold values. On average, the difference of incidence between the two sectors is 1 percentage point towards transport (it ranges from -3 to +12 percentage points). Similarly, the intensity of energy poverty is found to be similar in both sectors. The intensity corresponds to the average weighted number of disadvantages among the energy poor.

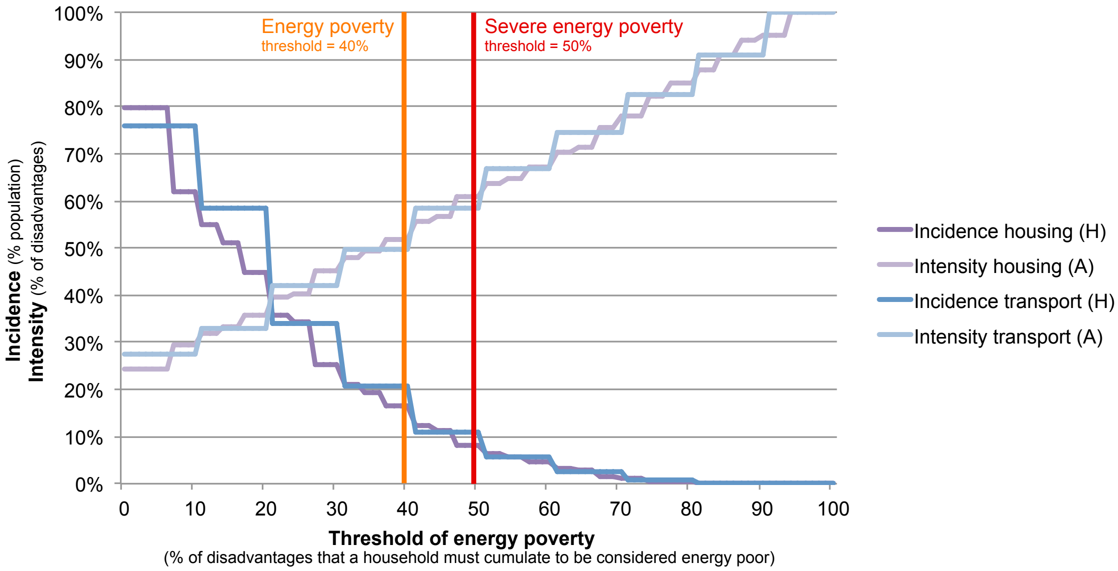

Figure 4: Incidence et intensity of multidimensional energy poverty for different thresholds

In both sectors, more than 75% of households are identified in at least one indicator (union approach) and no household (<1%) is disadvantaged in all indicators at the same time (intersection approach). Looking at the two sectors separately, 79% of households are disadvantaged in at least one indicator in housing and 76% in transport. These figures are large and probably include households that one does not want to categorise as energy poor - errors of inclusion. For example, a household that wants to extend the life of its car (which still works very well despite its age) or a couple of retirees who feel very comfortable at home at a temperature of 19°C both have a disadvantage in the MEPI, but it does not seem justified to consider them as energy poor.

As the threshold increases, households have to be identified in more and more indicators at the same time to be identified energy poor. The incidence first decreases rapidly, then slows down and converges to (almost) zero. In both sectors, the incidence becomes less than 1% from the threshold which corresponds to being disadvantaged in 70% of indicators. It excludes households that cumulate multiple disadvantages, but not as many, and that would deserve to be considered energy poor - errors of exclusion.

As such, a too low threshold leads to errors of inclusion, whereas a too high threshold leads to error of exclusion. The MEPI allows to choose intermediate thresholds. Such approach limits errors of inclusion and exclusion, as households have to be identified in several, but not all, indicators at the same time.

4.2. Selection of the energy poverty threshold

The choice of the threshold depends on the intensity of energy poverty situations that one wants to identify, i.e. the number of disadvantages that households cumulate. If such choice would deserve to be debated, in this paper, two thresholds are examined for the following reasons. They were selected to represent two levels of energy poverty. The first threshold, called the energy poverty threshold, is chosen to identify households disadvantaged in at least 40% of indicators. In other words, a household is energy poor if the weighted sum of the indicators in which it is disadvantaged is greater than or equal to 40%. For example, this means that in housing, a household is identified as energy poor if it cumulates:

- Poor dwelling energy performance and low income,
- Disproportionate energy expenditure, insufficient heating temperature and feeling cold.
- Low income, feeling cold, inadequate type of heating and no temperature control system.

Or in transport, a household is identified as energy poor if it cumulates:

- Disproportionate fuel expenditure and low income,
- Restriction of car use, no alternative to car and inefficient vehicle,
- No access to public transport, difficulty in meeting fuel costs and disproportionate fuel expenditure.

The second threshold, called the severe energy poverty threshold, is chosen so as to focus on the most disadvantaged group of households (approximately the 10% most disadvantaged). It corresponds to being disadvantaged in at least 50% of indicators. These households cumulate a higher number of disadvantages.

With the two thresholds selected, the incidence of energy poverty is slightly higher in transport than in housing (see figure 5). The share of households identified energy poor is 18% in housing and 21% in transport. With the threshold of severe energy poverty, the incidence falls to 9% and 11% respectively. Overall, 31% of households are energy poor in housing or transport, and 7% of households are energy poor in both sectors at the same time. It means that, among the energy poor, 24% of households face a double penalty in housing and transport (15% among the severe energy poor). Consequently, households affected in the housing sector are mostly different from those affected in the transport sector.

These results can be compared with existing reports on energy poverty in France. They are higher than the incidence reported by the statistical service of the Ministry

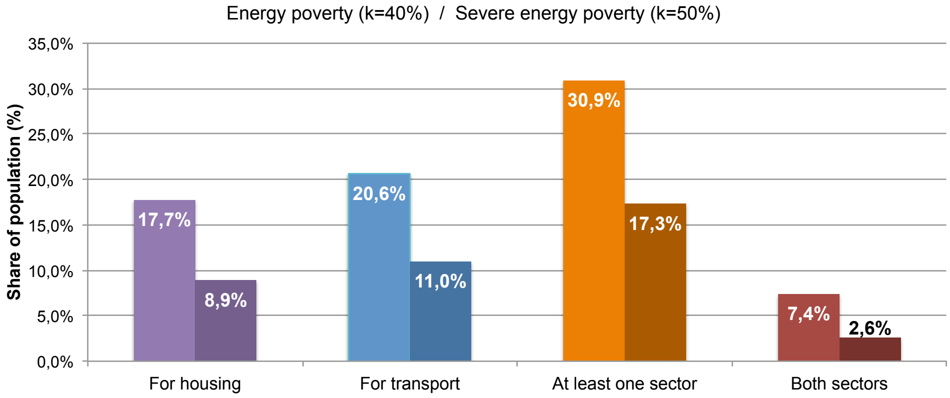

Figure 5: Incidence of multidimensional energy poverty in housing and transport

of the Ecological and Solidarity Transition in its report on SNTEDD[13], which identifies 14,6% of households in housing, 10,2% in transport, 22,2% in at least one sector and 2,6% in both sectors (Nirascou et al., 2016). Moreover, the situation is reversed between the two sectors. The MEPI identifies 1.2 times more households in transport than housing, whereas SNTEDD identifies 1.4 times more households in housing. However results in housing are lower than those estimated by the National Energy Poverty Observatory (ONPE), which identifies 20,4% of the population in a situation of energy poverty in housing (ONPE, 2016). These differences in results can be explained by the fact that the MEPI includes some but not all households identified by SNTEDD and ONPE - as some indicators are common: the energy expenditure ratio as well as feeling cold for ONPE - but also includes households identified by other non-monetary factors - which are not captured by SNTEDD and ONPE measures.

4.3. Comparison with the energy expenditure ratio

Currently, the most widely used indicator of energy poverty in the context of developed countries is the energy expenditure ratio (EER). I will first question whether the EER and the MEPI identify the same households, by comparing the overlap between the households identified by the MEPI and those identified by the EER. Then I will identify which dimensions of the MEPI are best covered by the EER and which dimensions it forgets, by evaluating the correlation between the EER and the different indicators of the MEPI. To identify energy poor households in the sense of the EER, I use the share of households' disposable income dedicated to energy (respectively fuels) with the threshold set at twice the national median[14].

[13] In France, the government has implemented a national strategy for the ecological transition towards sustainable development 2015-2020 (SNTEDD) under the energy transition law. Monitoring of the SNTEDD is ensured through a dashboard of 72 indicators, which includes one indicator on energy vulnerability (indicator E3.6). This indicator is similar to common energy poverty indicators: it measures the proportion of households whose share of energy expenditure for heating or commuting in income is more than twice the national median.

[14] The EER also corresponds one of the indicators included in the MEPI.

4.3.1. Level of overlap

Figure 6 shows the overlap between the EER and the MEPI, respectively in housing (left) and transport (right). The MEPI is found to capture the majority of households identified by the EER in housing and transport (83% and 73% respectively). The coverage rate is relatively high in this case, though not complete. It means most households disadvantaged in the EER tend to cumulate other disadvantages - otherwise they would not be identified by the MEPI. This result, however, is not entirely satisfactory. There remain households identified by the EER that are not identified by the MEPI because they cumulate little or no additional disadvantages. The mismatch is stronger in transport. It should be remembered that one of the criticisms of the EER based on actual energy expenditure is to identify households that are over-consuming by choice - for example, households with a lot of electronic equipment or a swimming pool, or those with many leisure activities in remote location or who regularly go away on weekends. Because the MEPI is interested in the accumulation of disadvantageous factors, it excludes these households, thus limiting the inclusion errors alleged against the EER.

Conversely, looking at the EER, it captures relatively less of the households identified by the MEPI (65% in housing and 57% in transport respectively). An important number of households identified by the MEPI are not identified by the EER: exclusion errors represent 6% of the population in housing and 9% in transport. These households are identified by the MEPI, but they are not identified by the EER because they experience difficulties in other dimensions of energy poverty that the EER does not capture. Thus it indicates the EER forgets a part of the population in multidimensional energy poverty, in other words it leads to important errors of exclusion. According to this analysis, exclusion errors are about twice as important as inclusion errors.

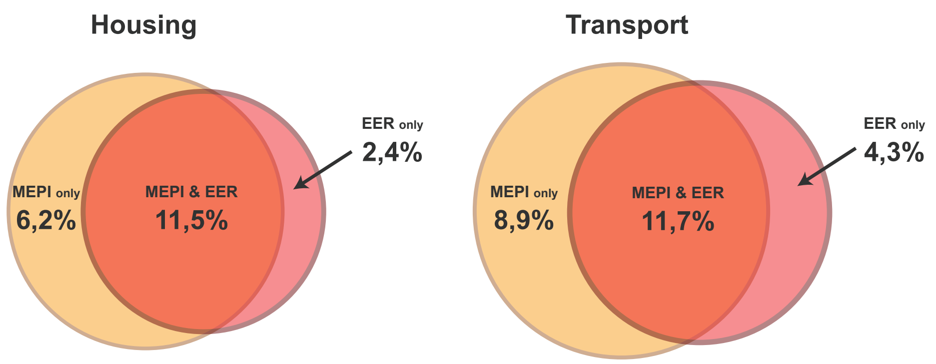

Figure 6: Overlap between the energy expenditure ratio (EER) and the MEPI

4.3.2. Correlation with non-monetary dimensions

Table 7 presents the Spearman correlation coefficients[15] between the EER and the MEPI indicators, as well as with the MEPI itself - for housing and transport. The Spearman coefficient allows to measure the association between two ordinal variables. On the housing side, this coefficient - and therefore the association - is weak, except in two cases. It is higher for income (0.31) and dwelling energy performance (0.23). This shows that the EER is best correlated with monetary resource indicators[16]. For other indicators, it falls below 0.05: felt cold, indoor temperature, energy efficiency of appliances and presence of a temperature control system. It is even negative for the type of heating (-0.05). Thus, the EER is poorly correlated with non-monetary resource indicators and indicators that directly evaluate an energy service.

On the transport side, coefficients are on average higher than in housing. They are greater than 0.05 except for car energy efficiency. Since the latter variable has an important missing value rate (13%), it is not possible to conclude on its apparent low association with the EER.

Housing

	EER
Income	0,31
Energy expenditure ratio	1,00
Feeling cold	0,05
Indoor temperature	0,03
Dwelling energy performance	0,23
Energy efficiency of appliances	(0,05)
Presence of a temperature control system	0,00
Type of heating	0,02
MEPI housing	0,69

Transport

	EER
Income	0,13
Fuel expenditure ratio	1,00
Restriction of car use	0,13
Difficulty in meeting fuel costs	0,22
Car energy efficiency	0,00
Alternative to car	0,28
Access to public transport	0,08
MEPI transport	0,58

Figure 7: Spearman correlation between the energy expenditure ratio (EER) and indicators of the MEPI.

The comparison between the two sectors reveals two things. First, the EER is less associated with income in transport (0.13) than in housing (0.31). This is consistent with the fact that the distribution of household fuel expenditure is less regressive in transport. Second, the indicators with which the EER is most closely correlated are the absence of an alternative to the car (0.28) on the transport side and the energy performance of housing (0.23) on the housing side - outside income. This result highlights that in order to reduce the energy burden on households, improving housing and mobility conditions is key. In particular, priority should be given to: developing alternatives to individual motorised transport and renovating the housing stock.

Lastly, this analysis shows the EER fails to capture some dimensions of the energy poverty experienced by households in housing and transport. It poorly identifies

[15] The value of an indicator corresponds to ordinal data: it takes the value 0 if non identified and 1 if identified. The Spearman correlation coefficient is a rank-based correlation compatible with ordinal data. As such it allows to measure the association between the different indicators of the MEPI.

[16] As a reminder, in the MEPI, building energy performance is calculated with real energy consumption for one third of households, rather than theoretical consumption, due to the lack of available data. It is therefore not a purely technical feature of the building for these households.

disadvantages in non-monetary indicators and energy services. Based on our data, the correlation is either low or non-existent with housing and mobility conditions, equipment and restriction ([-0.05;0.23] in housing and [0.00;0.28] in transport).

4.4. Composition of energy poverty

Policy makers need to know what lies behind energy poverty in order to characterise affected populations and to target policy responses. I will first highlight differences with income poverty, by quantifying the inclusion and exclusion errors of using income poverty as a criteria to target energy poverty policies. Then I will evaluate the incidence of energy poverty within different subpopulations in housing and transport respectively. To identify the income poor, I use disposable income per consumption unit and the official poverty line set at 60% of the national median income.

4.4.1. Differences with income poverty

Figure 8 indicates the extent of inclusion and exclusion errors of using income poverty to reach the energy poor identified by the MEPI. Exclusion errors refer to energy poor that would be ignored, while inclusion errors refer to some non energy poor that would be eligible. On the left are shown the share of the population according if they are energy poor or not, and if they are income poor or not. On the right are presented conditional probabilities knowing income poverty. In particular, given that a household is not income poor, it shows the probability that it will be identified as energy poor. Conversely, knowing that a household is not monetary poor, it shows the probability that it will not be identified as energy poor.

Share of population

Housing

	Non energy poor	Energy poor	Total
Non income poor	76%	11%	87%
Income poor	6%	7%	13%
Total	82%	18%	100%

Transport

	Non energy poor	Energy poor	Total
Non income poor	72%	15%	87%
Income poor	7%	6%	13%
Total	79%	21%	100%

Conditional probability (knowing monetary poverty)

Housing

	Non energy poor	Energy poor	Total
Non income poor	87%	13%	87%
Income poor	46%	54%	13%
Total	82%	18%	100%

Transport

	Non energy poor	Energy poor	Total
Non income poor	83%	17%	87%
Income poor	55%	45%	13%
Total	79%	21%	100%

Figure 8: Income poverty and multidimensional energy poverty in housing and transport

In both sectors, the probability that an income poor household is identified as energy poor is 46% in housing and 55% in transport. However, this situation affects less than 6% (respectively 7%) of the total population in housing (respectively in transport). Thus potential inclusion errors of using income poverty is low - relative to the total population. This result holds both the housing and transport sectors. On the other hand, looking at exclusion errors, the divergence has more consequences. The probability that a non income poor is identified as energy poor is 13% in housing and 17% in transport. The larger divergence in transport is partly explained by the larger gap between the incidence of income poverty (13%) and of energy poverty in transport (21%) - so that less overlap can be expected between the two indices - and because energy poverty in transport affects to a larger extent lmiddle class households, in addition to the poorest (see Appendix C). This situation concerns 11% (respectively 15%) of the total population in housing (respectively in transport). Thus, according to the MEPI, potential exclusion errors of using income poverty to target energy poverty policies is high. Among energy poor, the majority is not income poor for both sectors.

4.4.2. Incidence of energy poverty within sub-populations

Results are then broken down by sub-populations to show the incidence of energy poverty among and within these groups. Energy poverty is evaluated in housing and transport according to the following socio-economic characteristics: by household composition (single, single parent, couple, couple with children), by tenure status (renter / owner), by standard of living (D1 to D10), by residential location (urban poles / sparsely populated areas), by age range (<30 years old, 30-40 years old,..., >80 years old) and by climatic zones (H1a to H3 as described on figure 9, as well as Paris separated from the H1a zone). Figure 10 enables to graphically compare the incidence of energy poverty among these sub-populations.

The incidence of energy poverty varies with the standard of living. First of all, by construction, there is a sharp drop in the incidence between deciles 3 and 4. However, among the first three deciles, the evolution is contrasted. It gradually decreases in housing, while it is relatively stable in transport. The poorest are more severely affected in housing, while lower middle classes are similarly affected in both sectors. For upper deciles, households are more affected in transport. It is interesting to note that the incidence is not null for the highest deciles of income (deciles 8-9-10). Although it is difficult to describe them as energy poor, these households nevertheless cumulate enough disadvantageous factors - excluding income - to make their energy situation precarious[17].

The incidence of energy poverty also varies with other socio-economic characteristics. In transport, the sub-populations most affected by energy poverty are those living in sparsely populated areas, households with children and working-age households (<60 years old). In housing, the sub-populations most affected by energy poverty share similar geographical characteristics - those living in sparsely populated areas - but they differ in terms of age and household composition. Energy poverty in housing affects to a greater extent elderly households (>70 years old) and single households. In terms of tenure status, renters are more affected than owners in both sectors and especially in housing where the difference is larger. Results are more spread between the different

[17] Among the three highest deciles, less than 5% of households are energy poor in housing and less than 8% are energy poor in transport. In housing, the dwelling energy performance is what contributes the most (>40%) to their identification as energy poor. This contrasts with the lowest deciles of income (deciles 1-2-3), for whom the dwelling energy performance is the third contributor to energy poverty, after income and the energy expenditure ratio. In transport, car energy efficiency (41%) and poor mobility conditions (35%) are what contribute the most to the identification of the highest deciles of income as energy poor. As a reminder, car energy efficiency is proxied with fiscal power, which also translates the fact that richer households generally own more powerful cars - such as sport utility vehicles - than poorer households. For the rest of the population, results are more spread between the different dimensions of energy poverty.

climatic zones, except for Paris which is about twice less impacted than the rest of France in both sectors. Figure 11 presents, for each sub-population, the uncensored disadvantage rates of the housing and transport indicators of the MEPI, which describes which population groups are most affected by which indicators. These results are further detailed in Appendix C.

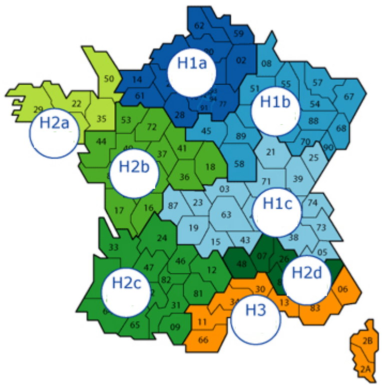

Figure 9: Climatic zones in France as defined by thermal regulation 2012 (RT2012)

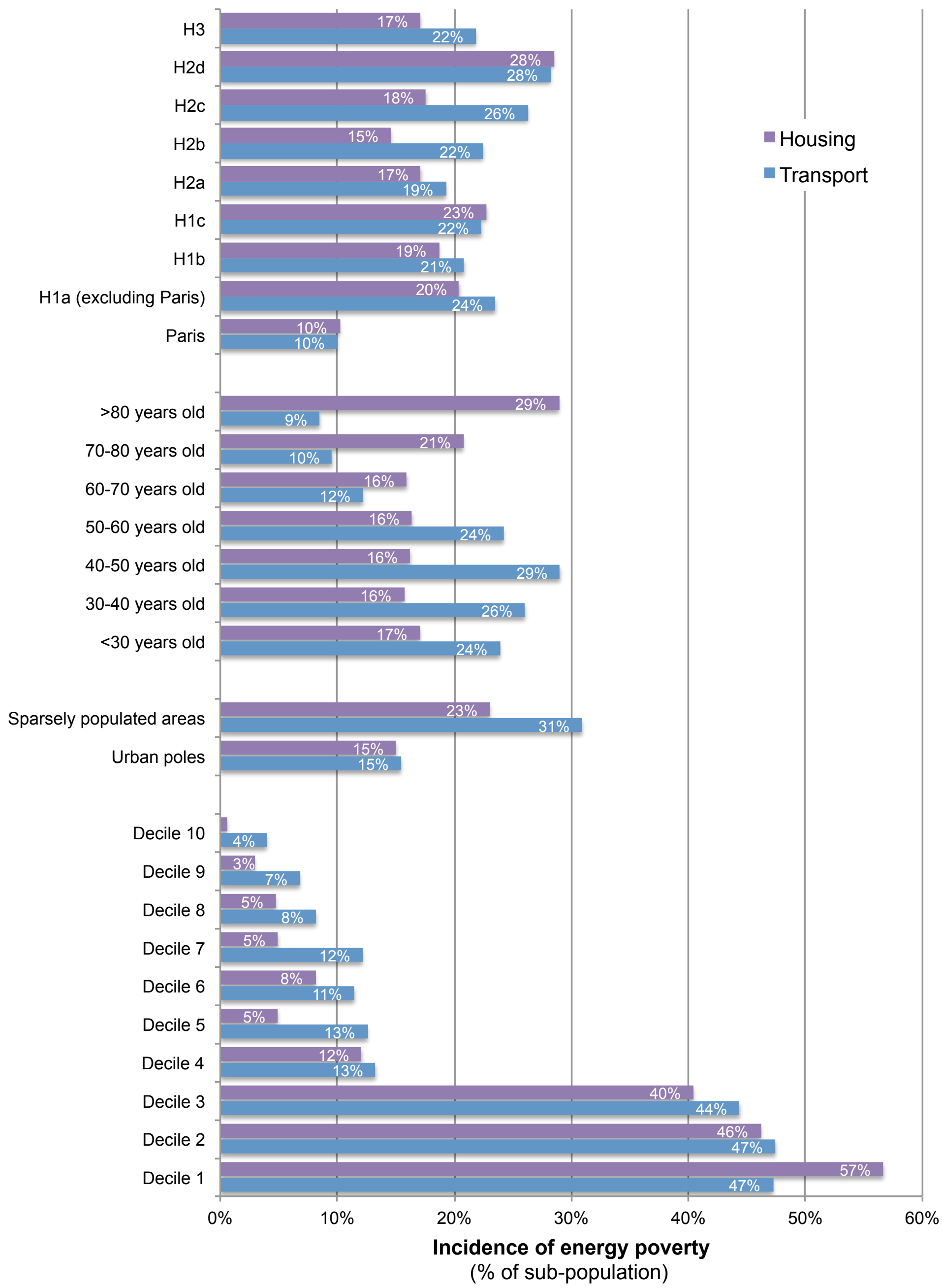

Figure 10: Incidence of energy poverty (H) for different sub-populations

	Housing								Transport						
	Income	Energy expenditure ratio	Felt cold	Indoor temperature	Dwelling energy performance	Energy efficiency of appliances	Temperature control system	Type of heating	Income	Fuel expenditure ratio	Restriction of car use	Difficulty in meeting fuel costs	Car energy efficiency	No alternative to car	No access to public transport
Total population	29%	14%	14%	23%	19%	22%	25%	13%	30%	16%	18%	12%	15%	33%	25%
D1	100%	45%	21%	27%	20%	20%	36%	12%	100%	29%	20%	18%	15%	17%	19%
D2	100%	25%	22%	27%	20%	23%	34%	13%	100%	22%	23%	21%	16%	28%	23%
D3	100%	24%	18%	23%	23%	20%	24%	13%	100%	16%	22%	17%	15%	27%	28%
D4	0%	16%	16%	21%	22%	21%	27%	16%	0%	21%	24%	14%	16%	35%	24%
D5	0%	10%	13%	24%	16%	24%	26%	15%	0%	17%	18%	13%	16%	35%	24%
D6	0%	9%	15%	24%	22%	22%	25%	16%	0%	17%	17%	12%	14%	41%	32%
D7	0%	5%	10%	22%	18%	22%	24%	13%	0%	13%	15%	8%	17%	39%	27%
D8	0%	5%	9%	19%	16%	21%	24%	12%	0%	12%	19%	6%	11%	39%	26%
D9	0%	3%	9%	22%	20%	22%	19%	11%	0%	9%	12%	4%	15%	37%	25%
D10	0%	1%	6%	19%	18%	20%	15%	9%	0%	3%	9%	4%	15%	30%	23%
Urban poles	30%	11%	15%	23%	15%	22%	27%	8%	30%	12%	14%	10%	15%	25%	12%
Sparsely populated areas	28%	19%	12%	23%	28%	22%	21%	24%	28%	25%	26%	15%	15%	48%	53%
Paris	22%	6%	18%	22%	18%	19%	34%	4%	30%	16%	18%	12%	15%	33%	25%
H1a (exc. Paris)	31%	18%	16%	25%	22%	29%	15%	16%	31%	20%	26%	16%	15%	41%	22%
H1b	28%	17%	13%	15%	23%	24%	19%	14%	29%	17%	16%	13%	13%	35%	30%
H1c	26%	18%	12%	19%	29%	18%	23%	15%	26%	17%	19%	11%	13%	40%	35%
H2a	30%	11%	12%	40%	13%	20%	18%	17%	30%	13%	22%	10%	13%	33%	26%
H2b	26%	13%	10%	25%	15%	23%	26%	14%	26%	20%	20%	12%	14%	39%	27%
H2c	32%	15%	11%	24%	19%	21%	32%	19%	32%	17%	20%	12%	15%	34%	50%
H2d	47%	16%	18%	22%	25%	12%	34%	15%	48%	14%	24%	13%	19%	23%	33%
H3	37%	12%	15%	20%	9%	19%	33%	11%	37%	17%	11%	11%	19%	34%	21%
<30 years old	30%	10%	18%	24%	16%	30%	26%	13%	38%	24%	10%	13%	16%	33%	13%
30-40 years old	33%	11%	17%	17%	16%	26%	22%	14%	31%	24%	18%	17%	15%	49%	20%
40-50 years old	28%	12%	14%	18%	17%	21%	27%	14%	34%	20%	23%	15%	15%	53%	24%
50-60 years old	23%	14%	9%	29%	23%	15%	23%	15%	28%	18%	22%	14%	16%	46%	25%
60-70 years old	24%	19%	8%	37%	28%	15%	27%	12%	23%	9%	19%	8%	14%	14%	30%
70-80 years old	35%	11%	19%	19%	15%	30%	28%	8%	24%	4%	17%	6%	14%	4%	33%
>80 years old	30%	30%	8%	23%	31%	8%	26%	13%	30%	2%	9%	3%	16%	1%	38%
Owner	19%	12%	7%	23%	22%	21%	21%	17%	19%	15%	19%	9%	15%	38%	33%
Renter	44%	15%	24%	22%	15%	23%	32%	8%	45%	17%	17%	16%	15%	27%	13%
Single	31%	23%	17%	25%	22%	14%	30%	10%	32%	15%	13%	9%	15%	15%	22%
Single parent	64%	32%	23%	21%	15%	25%	35%	13%	65%	19%	19%	15%	11%	31%	15%
Couple	19%	11%	9%	23%	22%	20%	23%	14%	20%	13%	20%	10%	15%	27%	30%
Couple with children	32%	7%	14%	20%	16%	30%	22%	16%	33%	20%	21%	16%	15%	57%	25%

Value > population mean

Figure 11: Non censured disadvantage rates for different sub-populations

5. Discussion and conclusion

Indicators are the basis on which to quantify energy poverty, to identify the affected population and to design support policies. Though there is a large consensus on the multidimensional nature of energy poverty, policy makers generally rely on a budgetary approach, and in particuler the energy expenditure ratio (EER). This choice is debated and has strong political implications. In this study, I designed a multidimensional energy poverty index (MEPI) which captures the energy poverty experienced by households in five dimensions: energy spending, restriction, housing/mobility conditions, equipment and standard of living. I first compared results of the MEPI with the EER. Results show the EER is not completely satisfactory for two reasons. First, the overlap between households identified by the EER and the MEPI is only partial: the EER excludes 35% and 43% of households identified by the MEPI in housing and transport, which represents respectively 6% and 9% of the population. These inclusion and exclusion errors could misguide the targeting of support policy. Second, the EER also fails to cover some dimensions of energy poverty. The correlation between the EER and the non-monetary indicators of the MEPI is either low or non-existent, particularly with housing and mobility conditions, households' equipment and restriction. it could distort the evaluation of related support policies. These findings suggest the EER constitutes a poor proxy for evaluating energy poverty in its multiple dimensions.

This study also highlights some important aspects of energy poverty. First, it confirms that income is an important dimension of energy poverty. Lack of income can lead some households to restrict their heating, their use of appliances or their mobility. Financial resources are thus essential to enable households to satisfy essential energy services and to enable them to adapt to the energy transition - if these opportunities exist. Yet, it also shows that having an income above the poverty line does not guarantee that households will not be affected in some crucial aspects of energy poverty. According to the MEPI, using income poverty as a criteria to target policies excludes many households disdvantaged in other aspects of energy poverty. Exclusion errors are significant in both sectors and more frequent in transport. These households face difficulties to satisfy essential energy services though their income does not fall below the poverty line. Thus, while the monetary dimension of energy poverty is important and necessary, using income poverty as a criteria for targeting policies to support energy poor is not sufficient. Results in the French context suggest that the targeting of support policies should be extented: 1/ to a broader range of income, such as to include low middle class households, especially in the transport sector, 2/ to vulnerable groups of population. In particular, the MEPI identifies that renters, single households and elderly households are particularly affected by energy poverty in housing. The MEPI also identifies that families and working-age households are particularly affected by energy poverty in transport. Finally, households living in sparsely populated areas are disproportionately affected by energy poverty both in housing and transport.

Most notably, this is the first study to my knowledge to develop a multidimensional measure of energy poverty based on the capability approach, in the context of developed countries. Results provide compelling evidence for quantifying energy poverty as a multidimensional concept and suggest that this approach constitutes a more comprehensive tool for evaluating energy poverty. I have shown existing indicators could distort the monitoring of the problem and the targeting of public policies as they hide some dimensions of energy poverty. In contrast, the MEPI limits the risks of inclusion and exclusion errors of one-dimensional indicators and it allows to account for the different dimensions of energy poverty. It follows that the adoption of a multidimensional measure would be useful for policy purposes, and that meanwhile, great care should be taken when interpreting results of existing indicators.

However, some limitations are worth noting. Multidimensional measures raise the question of their interpretability for public actors and society. The MEPI is data-intensive and more complex to implement. Yet the double threshold methodology brings some advantages over other composite indices. Its construction enables energy poverty to be monitored in each dimension and the populations most affected to be targeted.

As of today, the reproduction of the MEPI is limited by data availability. This study is based on a recent survey - the survey Phebus 2012 - that is richer in information on energy consumption and household energy behaviour than other existing databases. Results allow to analyse further energy poverty than was done to date. However, it is difficult to reproduce the MEPI regularly in France - the survey Phebus is a one time survey - or in other countries - no European countries have the necessary information to my knowledge. In France, the reproduction of the survey Phebus is not yet guaranteed. If not renewed, it would be desirable to integrate the relevant variables in other existing periodic surveys, such as the National Housing Survey (ENL) and the Family Budget Survey (BdF). This would also have the advantage of allowing regular monitoring of energy poverty. Such information could also be included in the SILC survey, which would enable to quantify and compare energy poverty at the European level.

In addition, it would be desirable to improve the reliability of some variables. In the application of this paper, some variables are partially reported - such as the building energy efficiency - other variables have limited interpretability - such as indoor temperature - while for other variables, I used proxy - such as fiscal power for car energy efficiency. As such, the reliability of some of the variables used could be improved and the introduction of additional variables could be considered, such as the accessibility of the living space, the hardship of journeys or indoor air quality.

More generally, in order to ensure appropriation of the MEPI by public actors, it would be essential to re-examine the relevance of the selected indicators. If this study draws on existing academic literature and reports, such choices result from value judgements rather than a pure technical exercise. It follows that the choice of relevant indicators, their relative weighting and thresholds for identification would deserve to be debated. The adoption of such indices calls for a consultation phase in order to specify and validate the relevant indices to be used.

Future work could include a detailed assessment of what constitutes energy poverty in different sub-populations. The factors that disadvantage energy poor may differ between socio-economic groups or territories. For instance, in the South of France, the incidence of energy poverty in housing is not far from average, though these households benefit from milder climate conditions. This would allow adapting the nature of policy responses to the need of specific groups. When implementing policy responses, reaching the energy poor also requires the identification of eligibility criteria. Valuable policy learnings could be drawn from a better understanding of energy poverty among different socio-economic groups and territories.

Alkire, S., Foster, J., 2011. Counting and multidimensional poverty measurement. Journal of Public Economics 95, 476–487. doi:10.1016/j.jpubeco.2010.11.006.

Alkire, S., Foster, J., Seth, S., Roche, J.M., Santos, M.E., 2015. Multidimensional Poverty Measurement and Analysis. Oxford University Press. Google-Books-ID: P8r9CAAAQBAJ.

Anderson, W., White, V., Finney, A., 2012. Coping with low incomes and cold homes. Energy Policy 49, 40–52.

Atkinson, A.B., 2003. Multidimensional deprivation: contrasting social welfare and counting approaches. The Journal of Economic Inequality 1, 51–65.

Atkinson, T., Cantillon, B., Marlier, E., Nolan, B., 2002. Social Indicators: The EU and Social Inclusion. OUP Oxford. Google-Books-ID: FX5iDnrgTg4C.

Bacqué, M.H., Fol, S., 2007. L'inégalité face à la mobilité: du constat à l'injonction. Revue suisse de sociologie 33, 89–104.

Beatty, T.K.M., Blow, L., Crossley, T.F., 2014. Is there a 'heat-or-eat' trade-off in the UK? Journal of the Royal Statistical Society: Series A (Statistics in Society) 177, 281–294. doi:10.1111/rssa.12013.

Berry, A., Jouffe, Y., Coulombel, N., Guivarch, C., 2016. Investigating fuel poverty in the transport sector: toward a composite indicator of vulnerability. Energy Research & Social Science 18, 7–20.

Bhattacharya, J., DeLeire, T., Haider, S., Currie, J., 2003. Heat or Eat? Cold-Weather Shocks and Nutrition in Poor American Families. American Journal of Public Health 93, 1149–1154. doi:10.2105/AJPH.93.7.1149.

Boardman, B., 1991. Fuel poverty: from cold homes to affordable warmth. John Wiley & Sons Ltd.

Boardman, B., 2013. Fixing Fuel Poverty: Challenges and Solutions. Routledge.

Bonnefoy, X., 2007. Inadequate housing and health: an overview. International Journal of Environment and Pollution 30, 411–429.

Bourguignon, F., Chakravarty, S.R., 2003. The Measurement of Multidimensional Poverty. The Journal of Economic Inequality 1, 25–49. doi:10.1023/A:1023913831342.

Bradshaw, J., Hutton, S., 1983. Social policy options and fuel poverty. Journal of Economic Psychology 3, 249–266. doi:10.1016/0167-4870(83)90005-3.

Braubach, M., 2011. Environmental burden of disease associated with inadequate housing: A method guide to the quantification of health effects of selected housing risks in the WHO European Region. World Health Organization .

Burr, M.L., 1999. Indoor air pollution and the respiratory health of children. Pediatric pulmonology 27, 3–5.

Charlier, D., Legendre, B., 2016. Fuel Poverty: A Composite Index Approach. FAERE Policy papers .

Day, R., Walker, G., Simcock, N., 2016. Conceptualising energy use and energy poverty using a capabilities framework. Energy Policy 93, 255–264.

EPEE, 2006. Diagnosis of causes and consequences of fuel poverty in Belgium, France, Italy, Spain and United Kingdom. Technical Report EIE/06/158/SI2.447367. EPEE.

Foster, J., Greer, J., Thorbecke, E., 1984. A Class of Decomposable Poverty Measures. Econometrica 52, 761–766. doi:10.2307/1913475.

Fullerton, D., 2008. Distributional Effects of Environmental and Energy Policy: An Introduction. Working Paper 14241. National Bureau of Economic Research. doi:10.3386/w14241.

Gicheva, D., Hastings, J., Villas-Boas, S., 2010. Investigating Income Effects in Scanner Data: Do Gasoline Prices Affect Grocery Purchases? The American Economic Review 100, 480–484. doi:10.2307/27805043.

Greening, L.A., Greene, D.L., Difiglio, C., 2000. Energy efficiency and consumption — the rebound effect — a survey. Energy Policy 28, 389–401. doi:10.1016/S0301-4215(00)00021-5.

Healy, J.D., 2003. Excess winter mortality in Europe: a cross country analysis identifying key risk factors. Journal of Epidemiology and Community Health 57, 784–789.

Healy, J.D., Clinch, J.P., 2002. Fuel Poverty in Europe: A Cross Country Analysis Using A New Composite Measurement, in: Environmental Studies Research Series Working Papers.

Hills, J., 2011. Fuel poverty: the problem and its measurement. Technical Report 39270. London School of Economics and Political Science, LSE Library.

Hills, J., 2012. Getting the measure of fuel poverty: final report of the Fuel Poverty Review. Monograph.

Host, S., Grange, D., Mettetal, L., Dubois, U., 2015. Précarité énergétique et santé: état des connaissances et situation en Ile-de-France. Pollution atmosphérique .

Imbert, I., Nogues, P., Sevenet, M., 2016. Same but different: On the applicability of fuel poverty indicators across countries: Insights from France. Energy Research & Social Science 15, 75–85. doi:10.1016/j.erss.2016.03.002.

Jones, A.P., 1999. Indoor air quality and health. Atmospheric Environment 33, 4535–4564. doi:10.1016/

S1352-2310(99)00272-1.
Legendre, B., Ricci, O., 2015. Measuring fuel poverty in France: Which households are the most fuel vulnerable? Energy Economics 49, 620–628.
Liddell, C., Morris, C., 2010. Fuel poverty and human health: a review of recent evidence. Energy policy 38, 2987–2997.
Liddell, C., Morris, C., Thomson, H., Guiney, C., 2016. Excess winter deaths in 30 European countries 1980–2013: a critical review of methods. Journal of Public Health 38, 806–814. doi:10.1093/pubmed/fdv184.
Lucas, K., 2012. Transport and social exclusion: Where are we now? Transport policy 20, 105–113.
Lucas, K., Mattioli, G., Verlinghieri, E., Guzman, A., 2016. Transport poverty and its adverse social consequences, in: Proceedings of the Institution of Civil Engineers-Transport, Thomas Telford (ICE Publishing).
Maidment, C.D., Jones, C.R., Webb, T.L., Hathway, E.A., Gilbertson, J.M., 2014. The impact of household energy efficiency measures on health: A meta-analysis. Energy Policy 65, 583–593. doi:10.1016/j.enpol.2013.10.054.
Mattioli, G., Lucas, K., Marsden, G., 2017. Transport poverty and fuel poverty in the UK: From analogy to comparison. Transport Policy 59, 93–105. doi:10.1016/j.tranpol.2017.07.007.
Milne, G., Boardman, B., 2000. Making cold homes warmer: the effect of energy efficiency improvements in low-income homes A report to the Energy Action Grants Agency Charitable Trust. Energy Policy 28, 411–424. doi:10.1016/S0301-4215(00)00019-7.
Moore, R., 2012. Definitions of fuel poverty: Implications for policy. Energy Policy 49, 19–26. doi:10.1016/j.enpol.2012.01.057.
Nirascou, F., Kleiber, F., Mosdale, L., 2016. Les indicateurs de la stratégie nationale de transition écologique vers un développement durable 2015-2020. CGDD SOeS .
Nussbaumer, P., Bazilian, M., Modi, V., 2012. Measuring energy poverty: Focusing on what matters. Renewable and Sustainable Energy Reviews 16, 231–243. doi:10.1016/j.rser.2011.07.150.
Okushima, S., 2017. Gauging energy poverty: A multidimensional approach. Energy 137, 1159–1166. doi:10.1016/j.energy.2017.05.137.
ONPE, 2016. Chiffres-Clés de la précarité énergétique. Technical Report.
Orfeuil, J.P., 2004. Accessibilité, mobilité, inégalités: regards sur la question en France aujourd'hui. Transports, pauvretés, exclusions: pouvoir bouger pour s'en sortir, París, Éditions de l'Aube .
Parry, I.W., Sigman, H., Walls, M., Williams III, R.C., 2005. The incidence of pollution control policies. NBER Working Paper doi:10.3386/w11438.
Sen, A., 1976. Poverty: An Ordinal Approach to Measurement. Econometrica 44, 219–231. doi:10.2307/1912718.
Sen, A., 1992. Inequality Reexamined. Harvard university press ed.
Simcock, N., Walker, G., Day, R., 2016. Fuel poverty in the UK: beyond heating? People, Place and Policy 10, 25–41.
Sorrell, S., Dimitropoulos, J., Sommerville, M., 2009. Empirical estimates of the direct rebound effect: A review. Energy policy 37, 1356–1371.
Stiglitz, J., Sen, A., Fitoussi, J.P., 2009. Rapport de la Commission sur la mesure des performances économiques et du progrès social. Rapport public.
Thomson, H., Bouzarovski, S., Snell, C., 2017. Rethinking the measurement of energy poverty in Europe: A critical analysis of indicators and data. Indoor and Built Environment , 1420326X17699260doi:10.1177/1420326X17699260.
Thomson, H., Snell, C., 2013. Quantifying the prevalence of fuel poverty across the European Union. Energy Policy 52, 563–572. doi:10.1016/j.enpol.2012.10.009.
Tirado Herrero, S., 2017. Energy poverty indicators: A critical review of methods. Indoor and Built Environment 26, 1018–1031. doi:10.1177/1420326X17718054.
Waddams Price, C., Brazier, K., Wang, W., 2012. Objective and subjective measures of fuel poverty. Energy Policy 49, 33–39. doi:10.1016/j.enpol.2011.11.095.
Walks, A., 2017. Driving the poor into debt? Automobile loans, transport disadvantage, and automobile dependence. Transport Policy doi:10.1016/j.tranpol.2017.01.001.
Wilkinson, P., Smith, K.R., Davies, M., Adair, H., Armstrong, B.G., Barrett, M., Bruce, N., Haines, A., Hamilton, I., Oreszczyn, T., Ridley, I., Tonne, C., Chalabi, Z., 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. The Lancet 374, 1917–1929. doi:10.1016/S0140-6736(09)61713-X.

Appendix A - Literature review

Below is described existing mutidimensional measures of energy poverty in the academic literature.

- Healy and Clinch (2002) proposed a composite index based on a set of consensual indicators to measure energy poverty across Europe. They used six indicators among which three are subjective - they are based on household statements - and three are objective - they are based on factual characteristics. The subjective indicators are: inability to heat adequately, inability to pay energy bills and lack of adequate heating systems. The objective indicators are: presence of moisture on walls and/or floors, mould on window frames and absence of central heating. The choice to use consensual indicators is motivated by the limitations of the budgetary approach as well as by the lack of available data on household energy expenditure in European surveys. Six scenarios are compared with different weights for each indicator.

- This composite index was updated eleven years later by Thomson and Snell (2013). Due to changes in survey data, the composite index was reduced to three indicators: inability to heat adequately, unpaid bills, and presence of leaks, moisture or mould.

- Charlier and Legendre (2016) proposed a composite indicator which corresponds to the geometric mean of different indicators, rather than the arithmetic mean as in the two previous studies. They used three indicators : standard of living, housing energy efficiency and housing temperature.

- Okushima (2017) defined three dimensions of energy poverty : energy cost, income and energy efficiency of housing. The two first indicators are budgetary while the last one is objective. On this basis, he identifies a household is energy poor if only it is poor in all three dimensions.

- The last study by Nussbaumer et al. (2012) used a minimum threshold of deprivation in energy services to identify the energy poor. The analysis concerns five dimensions of energy poverty in the context of developing countries. These include cooking (type of cooking fuel and presence of hood/chimney), lighting (access to electricity), appliances services (ownership of a fridge), entertainment/education (ownership of a radio or television), communication (ownership of a phone land line or mobile phone).

Appendix B - Methodological insights

B.1 Useful properties of the double threshlod methodology

The construction of multidimensional measurements has been the subject of much research and applications since the 1980s. The double threshold methodology developed by Alkire and Foster (2011) is a recent contribution which brings many useful properties[18]. Alkire et al. (2015) offers a detailed description of the properties verified by these measurements. Four properties are particularly useful for the purpose of this study.

Subgroup decomposability. The index can be calculated and compared between different population groups, such as by standard of living, residential location, housing occupancy status, age group, or any other variables of interest available in the survey.

Replication invariance. The index adjusts to the size of the population on which it is calculated, allowing comparison between societies with different population sizes and societies whose population changes over time.

Dimensional decomposability. The index can be broken down into its different dimensions to reveal which dimensions contribute most to energy poverty in any regions or population group. This helps to inform policy makers by supporting the development of targeted public policies addressing the factors that make specific groups of households energy poor.

Monotonicity. The index is sensitive to the multiplicity of disadvantageous factors. The level of energy poverty increases if one or more energy poor households become disadvantaged in an additional dimension. This property is particularly useful in encouraging targeting the most disadvantaged households.

The last two properties - dimensional decomposability and monotonicity - are verified by the MEPI, but they are not verified either by the energy expenditure ratio indicator or by a composite index such as proposed by Healy and Clinch (2002). Finally, this methodology has the advantage that it can be applied to data of different natures: cardinal data - measurable numerical values -, ordinal data - numerical values of which only the order is significant -, and/or categorical data - non-numerical values that are categorised with names.

[18] One major application is the the Multidimensional Poverty Index (MPI), developed by the Oxford Poverty and Human Development Initiative (OPHI), which has been rapidly successful through its use by UNDP. This index - which analyses 10 indicators within 3 dimensions: health, education and living conditions - has been evaluated in more than 105 countries since 2010 and now monitors the United Nations Sustainable Development Goals (ODD 1.2.2). The MPI is a major advance over an index such as the Human Development Index (HDI), which analyzes the same dimensions but does not have the same properties. The HDI corresponds to the geometric mean of its three indicators which has several drawbacks, some of which are listed below. In particular, it is difficult to interpret - it does not reflect incidence or intensity. It assumes that its components are commensurable - an increase in one dimension can be substituted for an increase in another dimension. It can also be mentioned that it is not decomposable by sub-population - the HDI of a population does not correspond to the weighted average of the HDI of its sub-populations. Finally, it does not inform us on the joint distribution of individual conditions - its level is the same whether or not the populations concerned by each indicator are the same.

B.2 Mathematical formalization

The MEPI belongs to the FGT family. The MEPI measures energy poverty in d variables within a population of n households. Let $Y = [y_{ij}]$ be the matrix of achievements of size n x d. y_{ij} represents the achievement of household i in variable j. Thus each vector line $y_i = (y_{i1}, y_{i2}, ..., y_{id})$ represents the achievements of household i in the different variables. Each vector column $y_j = (y_{1j}, y_{2j}, ..., y_{nj})$ represents the distribution of the realizations of variable j within households.

The methodology allows to assign weights to the various indicators. A weighting vector $w = (w_1, w_2, ..., w_d)$ contains the weights applied to each variable j. The w_j are selected so that $\sum_{j=1}^{d} w_j = 1$.

Let z_j be the threshold in variable j. From these thresholds, it is possible to identify for each household whether or not it is disadvantaged in each variable. Let $G = [g_{ij}]$ be the disadvantage matrix of size n x d. The disadvantage matrix is derived from the achievement matrix as follows. If a household is disadvantaged in variable j, i. e. if $y_{ij} > z_j$, then $g_{ij} = w_j$. If it is not disadvantaged in variable j, i. e. if $y_{ij} z_j$, then $g_{ij} = 0$. The MEPI may contain categorical variables. In this case, the element in the achievement matrix is not numerical and the threshold corresponds to a set of conditions to be met.

From the disadvantage matrix, it becomes possible to calculate the vector column $C = (c_1, c_2, ..., c_n)$ which contains the rate of weighted disadvantage of each household. This vector summarizes the weighted disadvantages of each household. It is calculated as follows: $c_i = \sum_{j=1}^{d} g_{ij}$.

Next, multidimensional energy poor are identified from a threshold k>0. A household is said to be energy poor if its weighted disadvantage rate c_i is greater than the threshold k. Finally, a final vector is constructed $B(k) = (b_1(k), b_2(k), ..., b_n(k))$, called censored weighted disadvantage rate vector, wherein $b_i(k) = c_i$ if $c_i k$ and $b_i(k) = 0$ if $c_i < k$. Vector B is a censored version of vector C. The difference is that vector B affects zero disadvantage to households that are not identified as multidimensional energy poor.

Finally, I calculate different indices of the class FGT (Foster et al., 1984). In particular, two indices are calculated to summarize information on energy poor.

The first index corresponds to incidence H: it measures the proportion of households that are identified as multidimensional energy poor.

$$H = \frac{q}{n} \tag{2}$$

With q the number of energy poor households ($c_i k$) and n the total number of households in the population.

The second index corresponds to intensity A: it measures the average rate of censored weighted disadvantage $b_i(k)$, i. e. the average weighted disadvantage rate among households identified multidimensional energy poor.

$$A = \frac{1}{q} \sum_{i=1}^{n} b_i(k) \tag{3}$$

Appendix C - Additional results

C.1 Description of energy poverty in housing

C.1.1 Disadvantage rate

For each indicator, the share of households identified as "disadvantaged" in this indicator - called the disadvantage rate - is calculated.

In total population, the disadvantage rate is highest for the absence of a temperature regulator, household equipment and temperature in the dwelling. 25% of households do not have a control system to regulate the temperature of their dwelling. 23% of households are insufficiently heated compared to the recommended temperature (19°C or 20°C for households with elderly people, young children or disabled). 22% of households own recent energy-intensive appliances. 20% of households live in an energy-inefficient dwelling (>330 kWh/m2/year)[19]. 14% of households report that they suffered from indoor cold for at least 24 hours last winter. 14% of households have a disproportionate energy expenditure relative to their income. 13% of households frequently heat themselves with a polluting and/or inefficient type of heating. Finally, by definition, 29% of households belong to the first three deciles of living standards (the missing 1% results from households with missing values removed from the analysis).

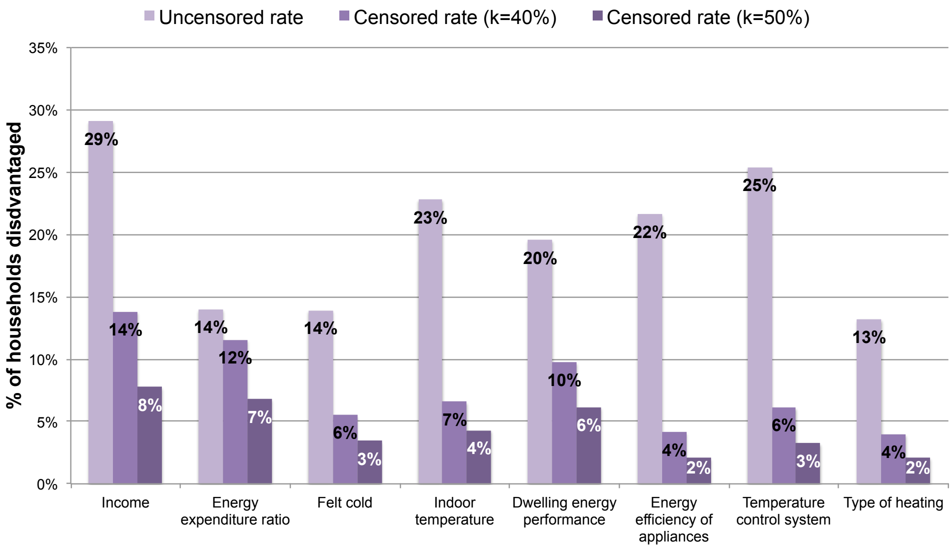

Figure 12: Disadvantage rate in housing indicators

The MEPI focuses on the censored disadvantage rate, i.e. the rate of households that are disadvantaged in this indicator while being identified as energy poor. It allows for

[19]This figure is less than 30% of dwellings classified F or G according to the energy performance certificate. As one third of households lacked information on their certificate, for these households, the energy efficiency indicator was calculated on the basis of their actual consumption, which explains the difference in outcome.

the monitoring of indicators among energy poor households. For example, the censored disadvantage rate in energy expenditure ratio is 12% while the uncensored rate is 14%. This means that 12% of households cumulate a high energy expenditure ratio and other disadvantages - otherwise they would not be identified as energy poor. This also means that 2% of households are identified in energy expenditure ratio but cumulate few or no additional disadvantages (this represents 14% of households idendified in energy expenditure ratio). Thus, I find that, although the majority, not all households identified in energy expenditure ratio are energy poor. More significantly, almost 4/5 of households identified in energy-intensive appliances are not energy poor. These households cumulate few or no additional disadvantages, so they are not identified as energy poor.

In the end, three disadvantage rates are calculated for each indicator. They are all calculated as a percentage of the total population. These are the uncensored rate (being identified), the censored rate at threshold 40% (being identified and energy poor) and the censored rate at threshold 50% (being identified and severe energy poor). Disadvantage rates of housing indicators are presented in figure 12.

C.1.2 Indicators contribution

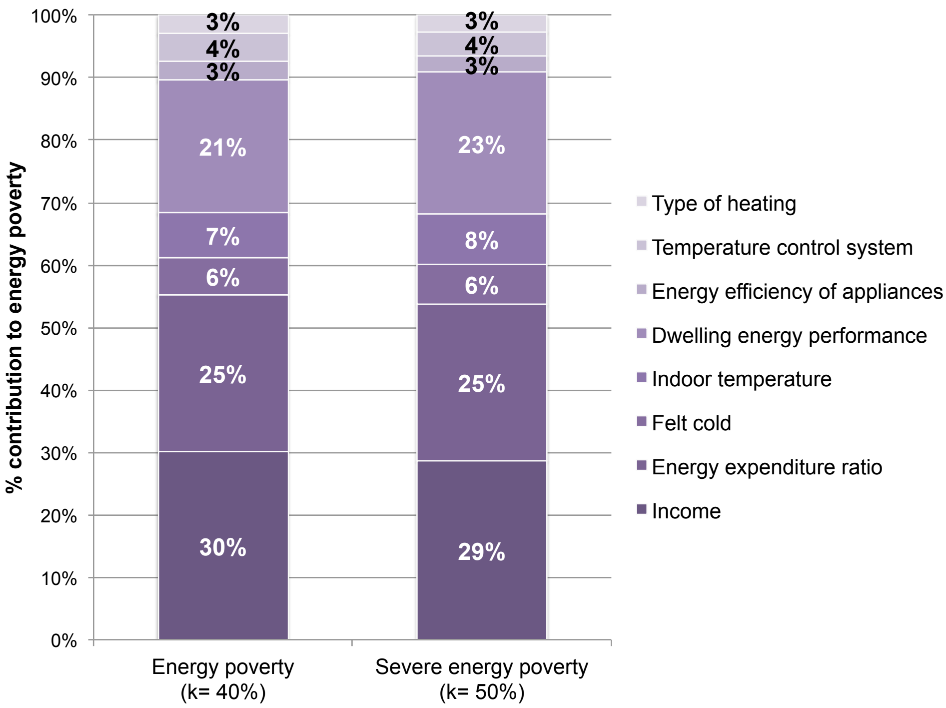

Figure 13: Contribution of each indicator to energy poverty in housing

Income, dwelling energy performance and energy expenditure ratio contribute most to multidimensional energy poverty. Figure 13 shows the contribution of each indicator to the housing MEPI. The contribution of each dimension is equal to the sum of the contributions of the indicators constituting that dimension. The contributions, in descending order, are: income (30%), energy spending (25%), housing conditions (21%), restriction (13%) and finally equipment (10%).

Looking at severe energy poverty, the relative contribution of each indicator changes only marginally: two contributions increase, while other contributions either remain stable or decrease. In particular, the contribution of dwelling energy performance and indoor temperature increase by 2 percentage points and 1 percentage point respectively, compared to energy poor. As such, their relative importance increases with the severity of energy poverty.

C.2 Description of energy poverty in transport

C.2.1 Disadvantage rate

In total population, the disadvantage rate is highest for the absence of alternative to car for commuting (33%) and the lack of access to public transport (25%). This is followed by the restriction of car use (18%), the fuel expenditure ratio (16%), the low car energy efficiency (15%) and the difficulty in meeting fuel costs (12%).

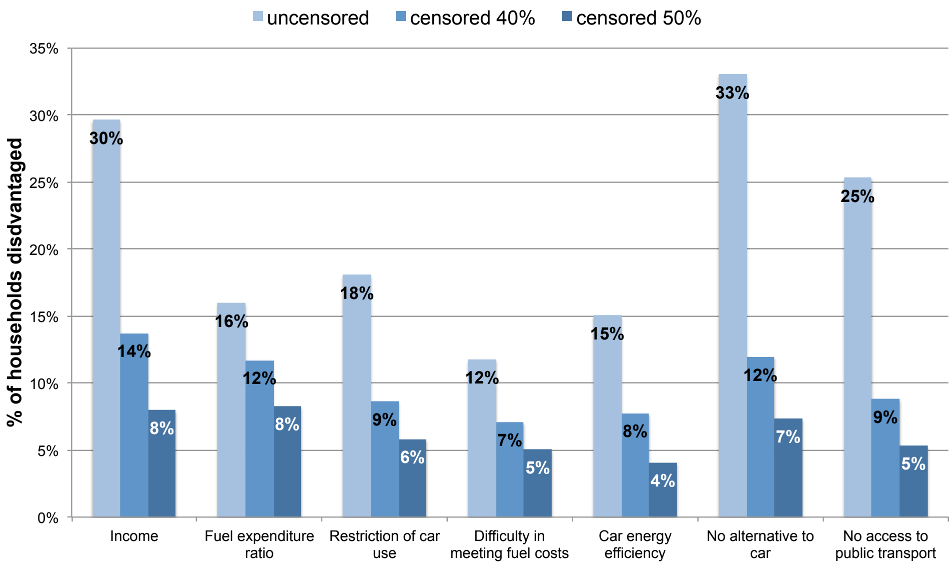

Figure 14: Disadvantage rate in transport indicators

The MEPI is built on the censored disadvantage rate. Compared to housing, fewer households identified in the expenditure ratio cumulate other disadvantages. In particular, 25% of households identified in fuel expenditure ratio are not identified energy poor (vs 14% in housing).

Again, three disadvantage rates are calculated for each indicator: the uncensored rate (being identified), the censored rate at threshold 30% (being identified and energy poor) and the censored rate at threshold 50% (being identified and severe energy poor). Disadvantage rates of transport indicators are presented in figure 14.

C.2.2 Indicators contribution

Income, mobility conditions and fuel expenditure ratio contribute most to multidimensional energy poverty. Figure 15 shows the contribution of each indicator to the transport MEPI. Contributions, in descending order, are: income (27%), fuel spending (23%), mobility conditions (21%), equipment (15%) and restriction (15%).

Similarly to the housing sector, looking at severe energy poverty, there are only small changes in relative contributions. Three contributions increase: fuel expenditure ratio

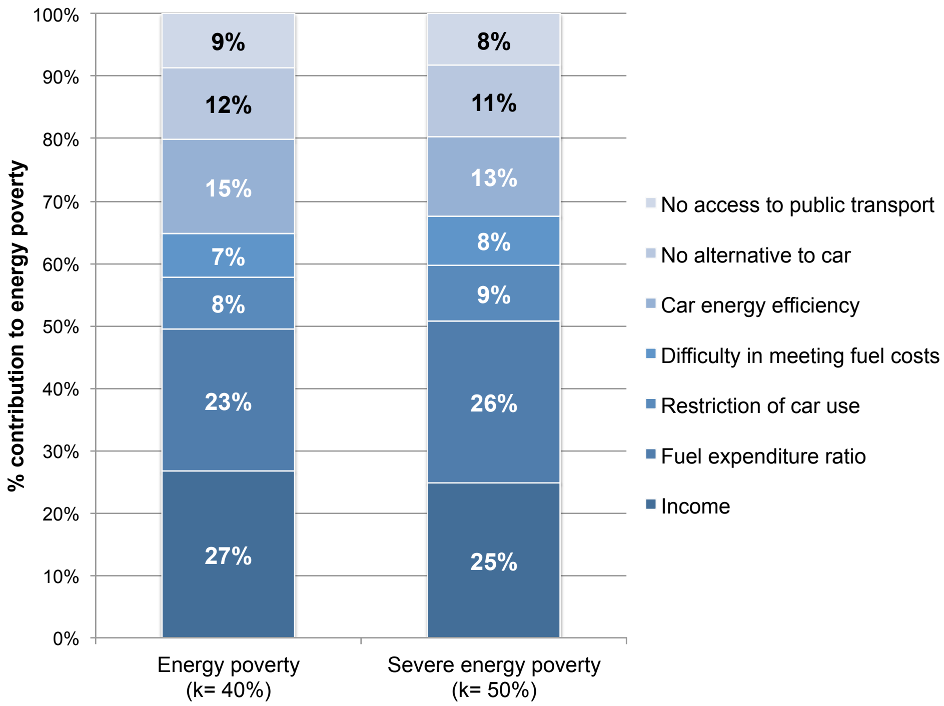

Figure 15: Contribution of each indicator to energy poverty in transport

(+3% points), difficulty in meeting fuel costs increase (+1% points) and restriction of car use (+1% points).

C.3 Breakdown by income decile

This section analyses the results of the MEPI in housing and transport by decile of standard of living. Figure 16 shows that the level of MEPI[20] varies with the standard of living. First of all, by construction, there is a sharp drop in the MEPI between deciles 3 and 4. However, among the first three deciles, the evolution of the MEPI is contrasted. It gradually decreases in housing, while it is relatively stable in transport. Thus, the poorest are the most affected in housing, while the lower middle classes are similarly affected in both sectors. On the contrary, for upper deciles, households are more affected in transport.

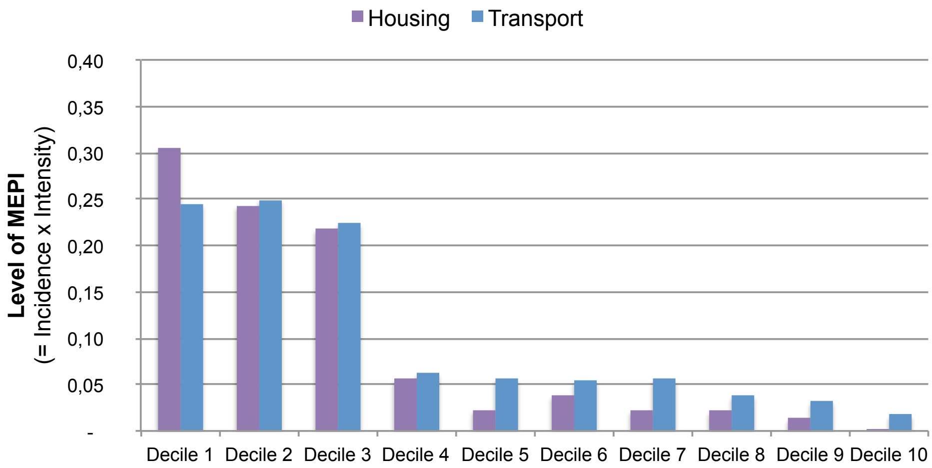

Figure 16: Level of MEPI according to households' income deciles in housing and transport

Figure 17 shows the incidence and intensity of energy poverty per income decile. The intensity varies relatively less between deciles (from 41% to 54%) compared with the incidence (from 1% to 57%). One reason is that the majority of households cumulate several but not all disadvantages. Yet deciles 1-2-3 are more disadvantaged on average. Their energy poverty intensity is above 50% while it decreases to 41% for higher deciles, which corresponds to being identified in one to three fewer factors on average (depending on the weight of these factors). For housing, households from decile 1 are the most prevalent energy poor, while for transport, the incidence is similar among deciles 1, 2 and 3. In the end, among the lowest three deciles, more than 40% of households are energy poor - whether in housing or transport. In contrast, among the three highest deciles, less than 5% of households are energy poor in housing and less than 8% are energy poor in transport.

It is interesting to note that the level of MEPI is not null for the highest deciles of income (deciles 8-9-10). Although it is difficult to describe them as energy poor, these

[20] As a reminder, the MEPI value reflects the incidence and intensity of energy poverty. It is calculated by multiplying the share of households in energy poverty (incidence) and the average rate of weighted disadvantages among energy poor (intensity).

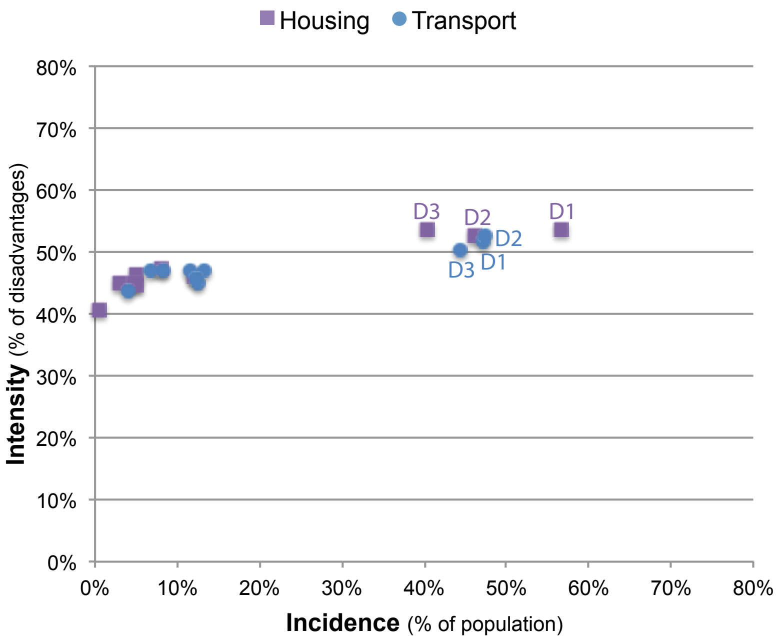

Figure 17: Incidence and intensity of energy poverty according to households' income deciles in housing and transport

households nevertheless cumulate enough disadvantageous factors - excluding income - to make their energy situation precarious. In housing, the dwelling energy performance is what contributes the most (>40%) to their identification as energy poor. This contrasts with the lowest deciles of income (deciles 1-2-3), for whom the dwelling energy performance is the third contributor to energy poverty, after income and the energy expenditure ratio. Finally for middle-class households (decile 4-5-6-7), the dwelling energy performance is again the major contributor, followed by the energy expenditure ratio. In transport, car energy efficiency[21] (41%) and poor mobility conditions (35%) are what contribute the most to the identification as energy poor of highest deciles of income. For the rest of the population, results are more spread between the different dimensions of energy poverty. The first decile of income is mostly affected by lack of income and high fuel expenditure (as in housing). Yet for deciles 2 and 3, poor mobility conditions, restriction and car energy efficiency contribute similarly with high fuel spending (contrary to housing) in addition to lack of income. As for middle-class households (decile 4-5-6-7), they are mostly affected by poor mobility conditions (as in housing) but also by high fuel spending (relatively more than in housing). Detailed description of percentage contribution of each indicator per income decile is given in table 5 for housing and table

[21] Due to issue of data availability in the survey Phebus, car energy efficiency is proxied with fiscal power, which also translates the fact that richer households generally own more powerful cars than poorer households.

6 for transport.

Table 5: Contribution of each indicators to energy poverty in housing per households' income decile (D1 to D10)

Housing indicators	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**	**D10**
Income	37%	38%	37%	0%	0%	0%	0%	0%	0%	0%
Energy expenditure ratio	29%	21%	22%	39%	33%	30%	22%	33%	25%	0%
Felt cold	5%	7%	6%	7%	7%	8%	8%	5%	7%	14%
Indoor temperature	6%	8%	6%	9%	11%	9%	11%	5%	8%	19%
Dwelling energy performance	13%	16%	21%	40%	39%	40%	43%	42%	44%	49%
Energy efficiency of appliances	2%	3%	3%	4%	2%	4%	4%	5%	6%	4%
Temperature control system	5%	5%	3%	5%	3%	4%	6%	6%	6%	7%
Type of heating	2%	3%	2%	5%	4%	5%	6%	5%	4%	7%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Table 6: Contribution of each indicators to energy poverty in transport per households' income decile (D1 to D10)

Transport indicators	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**	**D10**
Income	39%	38%	40%	0%	0%	0%	0%	0%	0%	0%
Fuel expenditure ratio	24%	18%	14%	35%	33%	32%	32%	34%	28%	18%
Restriction of car use	7%	8%	8%	12%	11%	8%	7%	10%	9%	4%
Difficulty in meeting fuel costs	6%	8%	7%	10%	10%	8%	4%	6%	6%	2%
Car energy efficiency	12%	13%	14%	16%	18%	20%	21%	19%	19%	41%
No alternative to car	6%	10%	9%	18%	18%	18%	19%	19%	20%	16%
No access to public transport	5%	6%	8%	9%	11%	14%	16%	13%	17%	19%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

C.4 Breakdown by sub-populations

This section analyses energy poverty in housing and transport according to different socio-economic characteristics: by household composition (single, single parent, couple, couple with children), by tenure status (renter / owner), by standard of living (D1 to D10), by residential location (urban poles / sparsely populated areas), by age range (<30 years old, 30-40 years old,..., >80 years old) and by climatic zones (H1a to H3, as well as Paris separated from the H1a zone).

Figure 10 presents, for each sub-population, the uncensored disadvantage rates of the housing and transport indicators of the MEPI, which allow to identify which population groups are most affected by which indicators.

In terms of residential location, households living in sparsely populated areas are the most affected in both sectors. In particular, the incidence of energy poverty is 1.5 times higher in housing and 2.1 times higher in transport compared to urban poles. The intensity of energy poverty is also higher in sparsely populated areas: +2 percentage points on the housing side and +4 percentage points on the transport side. Nevertheless, urban poles concentrate the majority of the population (67%), so that in total more than half of the energy poor live in an urban pole. The factors that contributes the most to energy poverty differ between the two types of residential location. In housing, the energy poverty experienced by households living in sparsely populated areas is relatively more attributed to the poor dwelling energy performance, the inadequacy of their type of heating and a high energy expenditure ratio, compared to the average population. On the opposite, the energy poverty experienced by households living in urban poles is relatively more attributed to the absence of a temperature control system and restriction. In transport, the energy poverty experienced by households living in sparsely populated areas is relatively more attributed to their poor mobility conditions (lack of access to public transport, no alternative to car), restriction and fuel expenditure ratio.

In terms of climatic zones, Paris is significantly less impacted by energy poverty than the rest of metropolitan France in both sectors. In housing, this can be explained by a lower per capita inhabited area and by the near absence of detached housing[22]. In transport, where the difference is even higher, the explanation lies in the large proportion of public transport and soft modes in Paris, which contrasts with the high dependence in car use in most other territories. The factors that contribute relatively more to energy poverty in Paris (compared to the national average) are feeling cold and lack of a temperature control system in housing. In transport, households living in Paris are less disadvantaged in all factors than the average population.

In terms of age range, energy poverty in housing affects to a greater extent elderly households (>70 years old), whereas in transport it affects mostly working-age households (<60 years old). In housing, this can be explained by the fact that elderly people spend more time at home and have lower resistance to the cold, so that they require a higher temperature to feel comfortable. The factors that contribute to their energy poverty are diverse and cover all five dimensions of MEPI. In transport, the higher incidence of energy poverty among working-age households can be explained by higher mobility needs among active people (in particular to commute) and households with children.

[22] Compared to apartment building, detached housing requires more heating to reach a given temperature due to a higher contact with the outside air.

The factors that contribute the most to their energy poverty are a high fuel expenditure ratio, restriction of car use (especially among households aged 40-60 years old), lack of alternative to car and low income.