WORKING PAPER

N° 2024-3

HOW TO MEASURE ENERGY POVERTY IN WARM AND COLD CLIMATE TERRITORIES? A MULTIDIMENSIONAL APPROACH

MANITRA RAKOTOMENA, OLIVIA RICCI

www.tepp.eu

TEPP – Theory and Evaluation of Public Policies - FR CNRS 2042

How to measure energy poverty in warm and cold climate territories? A multidimensional approach

Manitra Rakotomena[1] and Olivia Ricci[1]

ABSTRACT

Energy poverty currently affects a significant number of European citizens, representing a growing problem that needs to be addressed. The literature on energy poverty in developed countries has mainly focused on cold winter and heating issues. However, recent rising temperatures due to climate change are exposing an increasing number of people to a new form of housing vulnerability called 'summer energy poverty', with some households unable to keep their homes cool enough. The objective of the study is to provide a new measure of energy poverty to better identify those who suffer the most, whether they live in hot or cold weather countries. We develop a multidimensional indicator of energy poverty that for the first time includes a climatic dimension by considering thermal discomfort.

RESUME

La pauvreté énergétique affecte actuellement un nombre significatif de citoyens européens, représentant un problème croissant qui doit être traité. La littérature sur la pauvreté énergétique dans les pays développés s'est principalement concentrée sur les problèmes de froid hivernal et de chauffage. Cependant, l'augmentation récente des températures due au changement climatique expose de plus en plus de personnes à une nouvelle forme de vulnérabilité liée au logement appelée « pauvreté énergétique estivale ». L'objectif de l'étude est de fournir une nouvelle mesure de la pauvreté énergétique pour mieux identifier les ménages précaires, qu'ils vivent dans des pays à climat chaud ou froid. Nous développons un indicateur multidimensionnel de la pauvreté énergétique qui, pour la première fois, inclut une dimension climatique en tenant compte du confort thermique.

KEYWORDS: energy poverty, tropical territories, multidimensional approach, quality of housing, thermal discomfort, summer energy poverty

MOTS CLES : pauvreté énergétique, territoires tropicaux, approche multidimensionnelle, qualité du logement, inconfort thermique, pauvreté énergétique estivale

JEL CODES: Q4, I32

[1] Laboratoire CEMOI, University of La Réunion (FRANCE), 15 Av. René Cassin, Saint-Denis Cedex 9 97400, La Réunion ; andriandrazana.rakotomena@univ-reunion.fr, olivia.ricci@univ-reunion.fr

ABBREVIATIONS

AFCP: After Energy-Cost Poverty
DEPI: Thermal Discomfort and Energy Poverty Index
DI: Discomfort Index
DROM: Départements et Régions d'Outre-Mer (French overseas departments and regions)
FPI: Fuel Poverty Index
LIHC: Low-Income and High-Cost
ONPE: Observatoire National de la Précarité Energétique
PCU: Per Consumption Unit

1 INTRODUCTION

The concept of energy poverty was first conceived in the United Kingdom in the 1980s. Bradshaw and Hutton (1983) defined a energy-poor household as a household that is unable to achieve adequate heating in the home. In France and Europe, related literature focuses on cold winter and heating issues to define energy poverty. Devalière (2007) proposed the following definition in France: '*one who encounters a social, economic and environmental vulnerability which prevents him from heating himself appropriately and/or paying his energy bills'.* According to Simcock et al (2016), studies have widely examined the negative health impacts of living at cold temperatures (Boardman, 1991, 2010; Ormandy and Ezratty, 2012), including energy poverty's relation to the problem of 'excess winter deaths' (Liddell and Morris, 2010). From the early work of Bradshaw and Hutton (1983) to more recent research (e.g., Anderson et al., 2012; Middlemiss and Gillard, 2015; Walker and Day, 2012), studies have focused on people suffering from cold at home in winter (Simcock et al, 2016).

However, energy poverty also exists in summer, with some households unable to keep their homes cool enough. A recent study, published in June 2023 by the Abbé Pierre Foundation in France, revealed that more than half of French people suffered from heat in their homes at least once in 2022. This study calls this phenomenon 'summer energy poverty'. The study declares: '*The 5.2 million thermal colanders impossible to heat in winter turn into energy kettles impossible to cool in summer*'. In the last few decades, especially since the summer heat wave of 2003 in Europe, which caused more than 30,000 deaths across Europe (De Bono et al., 2004), research has been conducted on the health risks related to high temperatures. Similar to the case for cold temperature impacts, vulnerable people, such as children and older people, as well as people suffering from chronic diseases, such as diabetes or neurological disorders, were found to be more vulnerable to high temperatures (Madrigano et al., 2015; Vardoulakis et al., 2014). In France, between 2014 and 2022, 32,658 deaths were attributable to heat, including 23,080 deaths of people aged 75 and over. Twenty-eight percent of these deaths occurred during heat waves. The most were observed in 2022 (6,969 excess deaths, including 29% during heat waves) and 2019 (4,441 excess deaths, including 42% during heat waves) (Santé Publique France, 2023). This issue will be aggravated in the years to come due to climate change. Global warming increases the frequency, intensity and duration of heat waves, which is likely to lead to a rise in excess summer mortality (Fondation Abbé-Pierre, 2023; IPCC, 2013; Santé Publique France, 2023).

In the empirical literature, energy poverty is still largely associated with the feeling of cold in one’s accommodation, and too little attention has been given to housing discomfort linked to heat peaks. Indeed, the definition of energy poverty and the measures include indicators linked to the rate of energy effort and the feeling of cold but do not currently consider the difficulties in maintaining an acceptable temperature in one’s home during periods of heat. According to Sanchez-Guevara et al. (2019), there is a need to broaden current definitions of energy poverty. In countries with extreme summers or tropical climates, an extended definition of energy poverty that addresses the ability of a household to maintain indoor temperatures at safe levels during a period of high heat is necessary (Sanchez et al., 2017). Thus, cooling needs and overheating risk need to be incorporated into the energy poverty equation (Moore, 2012; Moore et al., 2017). The enhancement of the definition of energy poverty will lead to a better assessment of the problem and provide the opportunity to set better solutions for impacted vulnerable households. Measuring the extent of energy poverty in a territory and identifying the most vulnerable households are essential for the development of effective policy measures to combat energy poverty. However, the current literature and national practices in Europe do not propose a unique measurement of energy poverty. Consensus on a common definition and a measure of energy poverty that works in cold countries as well as in hot climates is needed. Moreover, harmonising the use of energy poverty indicators is still needed in developed countries.

In this paper, we provide a new way to better identify those who suffer the most from energy poverty, whether they live in cold or hot weather countries. Charlier and Legendre (2019) proposed a fuel poverty indicator (FPI) that considers three dimensions of energy poverty: monetary poverty, the energy efficiency of housing and heating restrictions. We draw on the indicator developed by Charlier and Legendre (2019) to construct a thermal discomfort and energy poverty index (DEPI) that, for the first time, includes a climatic comfort dimension enabling the measurement of energy poverty in warm climate regions. We believe that a better understanding can be developed through a multidimensional approach of energy poverty based on the relationship of three dimensions: i) monetary poverty, ii) dwelling quality and iii) climatic comfort conditions. We will apply our innovative multidimensional thermal discomfort and energy poverty index (DEPI) to four French overseas departments and regions (DROM)[2]: French Guiana, Guadeloupe, Martinique and Reunion Island. These territories are far from metropolitan France, but they have the same status as mainland France's regions and departments. In Guadeloupe, Reunion Island and Martinique, the climate is tropical, and the temperature varies little during the year. Summer is the hot and wet season. Winter is the milder and drier season. In French Guiana, the climate is equatorial. Precipitation is abundant during the summer. Heat and humidity are widely present across these territories.

[2] The French overseas departments and regions (départements et régions d'outre-mer, DROM) are French jurisdictions outside European (mainland) France. Guadeloupe and Martinique are located in the Caribbean, French Guiana in South America and Reunion Island in the Indian Ocean, off the coast of East Africa.

We contribute to literature in many ways. The first contribution is thematic, as we consider exposure to heat and its consequences in terms of health. The second contribution is methodological. We overcome a methodological difficulty in characterising energy poverty by proposing a multidimensional indicator (DEPI) that considers climatic comfort to measure energy poverty in winter and summer. We enhance existing indicators, as very few consider the environmental dimension. Finally, we propose an original application to French overseas regions and compare energy-poor people in four different regions. We also test the robustness of the composite indicator.

The broad scope of the DEPI indicator enables the comparison of energy poverty intensity in countries with different climate conditions over time. Our work will enable policymakers to adopt appropriate energy poverty control strategies and monitor the effectiveness of the strategies in the three dimensions of the composite indicator (monetary, housing quality, climatic comfort). Moreover, a strength of the indicator is that it enables the monitoring of the evolution of energy poverty related to climate change in the short and the long term. In the short term, it measures exposure to energy poverty in cases of exceptional heat or cold waves, and in the long term, it measures energy poverty under the global warming trend.

The paper is organised as follows. Section 2 presents a literature review on the concept of energy poverty in countries with warm climates and its measurement. In the third section, we develop the construction of the multidimensional indicator (DEPI). In section 4, we propose an application of the indicator to measure energy poverty in four French overseas tropical territories. We conclude in section 5.

2 LITERATURE REVIEW ON ENERGY POVERTY IN WARM CLIMATE TERRITORIES AND ITS MEASUREMENT

2.1 Literature on 'cooling poverty' or 'summer energy poverty'

Currently, the concept of energy poverty in the literature tends to focus on cold winters and heating issues in developed countries. Research on 'cooling poverty' or 'summer energy poverty' in Europe is in its infancy (Thomson et al., 2019). Indoor overheating problems have been identified in studies related to low-income households carried out in warmer European countries, such as Portugal (Barbosa et al., 2015), Greece (Sakka et al., 2012) and Spain (Sanchez et al., 2017), as well as heating-dominated countries, such as the UK (Mavrogianni et al., 2015; Taylor et al., 2016). Sanchez et al. (2017) proposed including energy cooling needs in the definition of energy poverty in Spain. A study on the issue of inadequate cooling in summer in European Union countries was performed by Thomson et al. (2019). They showed that people in all European Union countries reported difficulties in maintaining comfortable levels of cooling during summer even within countries that have milder climates and where this phenomenon was thought to be rare, such as the UK.

Limited empirical research has been conducted on energy poverty in tropical territories (Charlier et al., 2020; Mazzone, 2020). Tropical regions are characterised by constant heat and high humidity. By nature, they therefore do not experience winter periods but rather temperatures above the regional average and heavy rainfall. Mazzone (2020) studied energy poverty in the Amazon region of Brazil. They extended the definition of energy poverty to a situation in which households experienced an inability to provide energy services, lack of efficient thermal materials and/or passive systems in housing, and an inability to cope and adapt to heat or cold. Charlier et al. (2020) characterised energy poverty in four French overseas departments and regions (DROM):

Guadeloupe, French Guiana, Reunion Island and Martinique. As no definition or measure existed to characterise energy poverty in tropical territories, they proposed a latent class methodology to classify households into different categories: energy poor, energy vulnerable and energy sufficient. Tabata and Tsai (2020) measured the extent of energy poverty during the summer period in Japan, when temperatures can reach 35°C. Using the indicator of low-income high cost (Hills, 2011), they showed that energy-poor households prefer to eat at home, so they spend more on energy for cooling and cooking (electricity, gas, and other energy and light). Then, elderly couples and single parents are highly vulnerable to energy poverty, and many of them have old air conditioners that increase electricity expenditures. Research work also shows that social and economic factors play a major role in this phenomenon of excessive heat experienced: the risk of exposure, i.e., the fact that a household lives in poorly insulated housing in an 'urban heat island' (Sanchez-Guevara et al., 2019), the ability of people to react to excessive heat and their sensitivity to heat (Thomson et al., 2019). During the summer of 2022, a report by the Abbé-Pierre Foundation noted that 59% of French people suffered from heat in their house. Precarious urban populations and young and older people are those most affected by this 'summer energy poverty'(Abbé-Pierre Foundation, 2023).

2.2 The question of the measurement

In addition to the question of the definition of energy poverty arises the question of its measurement. Conducting a policy to reduce energy poverty requires a quantification of the extent of energy poverty in a territory. Moreover, policymakers need reliable measurement indicators to quantify the effectiveness of their policy *ex-post*. Depending on the indicators selected, the target population may vary, and the results of the policy may differ accordingly (Fizaine et Kahouli, 2019; Legendre and Ricci, 2015). While there is a large body of literature on measuring poverty, consensus has not been reached on a common measure, and some limits have been shown in the literature.

The indicators for measuring energy poverty are numerous. According to Charlier and Legendre (2021), they can be grouped into three categories: *budgetary and consensual approaches, subjective approaches* and *multidimensional approaches*.

Budgetary approaches involve assessing household income and energy expenditures. The most commonly used indicators are the 10% ratio (Boardman, 1991), the low-income and high-cost indicator (LIHC) and the after energy-cost poverty indicator (AFCP) (Hills, 2011, 2012). *Consensual approaches* involve assessing energy poverty by analysing the use of energy services that are necessary for a decent standard of living (Bouzarovski et al., 2012; Day et al., 2016). Choosing a threshold in budgetary approaches remains questionable. The 10% threshold, which represented twice the median energy expenditures in England in the 1990s, may not be suitable in other countries. There is also the problem of the halo around the threshold that is not considered with this indicator. A household may not be identified as energy poor because its energy effort ratio is just below the threshold. In addition, estimating energy expenditure does not capture households' restrictive behaviour, which is also a form of energy poverty (Dutreix et al., 2014).

Subjective approaches quantify the phenomenon through the way households feel about, for example, the cold in their homes or their ability to pay their energy bills. They bring together several factors (socioeconomic conditions, housing characteristics, income, energy expenditures) to assess energy poverty based on personal points of view. These approaches must be treated with caution, as they are based on self-reported responses.

Multidimensional approaches are constructed using composite indicators to quantify the phenomenon. The complexity of measuring energy poverty is due to its multidimensional nature

(ONPE, 2017). In particular, the phenomenon can be explained by several factors: the socio-economic conditions of the household, the energy efficiency of the dwelling and the conditions of access to energy. Several papers have highlighted the advantages of a composite indicator to measure energy poverty. One is its capacity to capture multidimensional concepts that cannot be appraised by a single indicator (Berry et al., 2016; Charlier and Legendre, 2019; ONPE, 2014). Siksnelyte-Butkiene et al. (2021) reported that there are 41 composite indicators proposed in the literature to measure energy poverty in developing and developed countries. In developed countries, different authors have proposed a composite indicator based on different aspects. Sokołowski et al. (2020) present the multidimensional energy poverty index that combines five subindicators: two objective indicators (low income - high costs and high actual costs) and three subjective indicators based on the feeling of cold, perceived housing quality and difficulties paying bills. Castaño-Rosa et al., (2019, 2020) presented the Index for Evaluation of Vulnerability to Energy Poverty, which includes five economic and social dimensions (monetary poverty indicator, energy indicator, comfort indicator, and health-related quality-life cost). Others have tried to focus on building characteristics, such as Fabbri (2015), who presented the building energy poverty index based on a building's energy performance. The index includes variables such as household income, energy prices, and building characteristics. Charlier and Legendre (2019) proposed a fuel poverty indicator (FPI), which is a geometric mean of an indicator of standard of living, an indicator of housing energy inefficiency and an indicator capturing the potential heating restriction by providing information about housing temperature.

None of the proposed indicators in the literature include a climatic dimension to capture household thermal comfort. However, we have highlighted that being exposed to heat waves, which may become increasingly frequent with climate change, can have dramatic effects on health.

We draw on the FPI indicator developed by Charlier and Legendre (2019) to develop our DEPI indicator. In fact, their methodology is clearly presented, and the FPI has the advantage of considering monetary poverty and housing quality, which seem essential to better understand energy poverty. However, as their indicator misses a climatic dimension (Siksnelyte-Butkiene et al., 2021), we propose to develop the indicator in this sense by introducing household exposure to temperature and humidity.

3 DEVELOPING A MULTIDIMENSIONAL INDICATOR OF ENERGY POVERTY

Drawing on the indicator of Charlier and Legendre (2019) explained in the previous section, the objective is to develop a measure of energy poverty that could be applied to warm and cold weather.

3.1 Construction of the thermal discomfort and energy poverty index (DEPI)

The thermal discomfort and energy poverty index (DEPI) captures three dimensions of energy poverty: *household standard of living*, *household housing quality* and *household climatic comfort*. It is well highlighted in the literature that energy poverty refers to the two first intertwined dimensions: the social and financial situation of a household and the state of its housing. The European Energy Poverty and Energy Efficiency (2008) report shows that energy-poor households have several common characteristics: their inability to pay energy bills and cold and damp living conditions as well as homes with low energy performance. The third dimension (household climatic comfort) that we want to highlight is, however, less known. According to Fanger (1970), temperature and humidity are heat stress factors that define the human sensation of thermal comfort. By considering temperature and humidity data, we calculate a discomfort index based on

Thom's work on discomfort index (1959). The dimensions of the DEPI indicator are shown in Fig. 1.

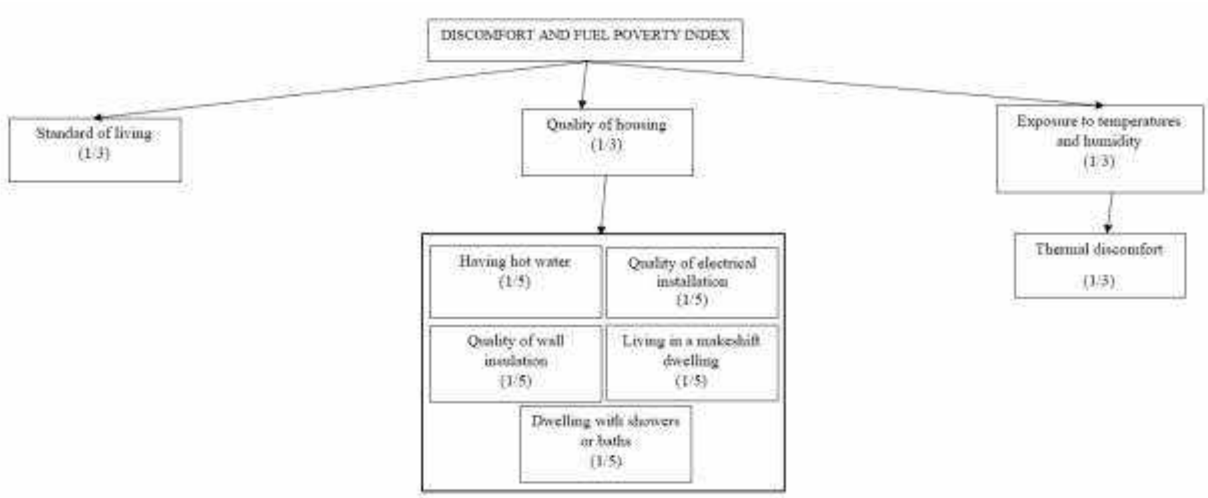

Fig. 1 Thermal discomfort and energy poverty index composition

Source: authors

The DEPI is based on a geometric mean of the three subindicators[3]:

$$DFPI_i = \sqrt[3]{I_{P,i} * I_{Q,i} * I_{C,i}} \#(1)$$

where $I_{P,i}$ is an indicator of household i's standard of living; $I_{Q,i}$ is an indicator of poor housing quality; and $I_{C,i}$ is an indicator of thermal discomfort. The geometric mean allows us to reduce the degree of compensability between the three dimensions (a low performance for an indicator cannot be offset by high values in other indicators) and ensures that a marginal variation in the indicator of income poverty has the same impact on the DEPI as the indicator of housing quality or that of exposure to temperature and humidity. Weights can have a significant impact on the overall

[3] In construction of the discomfort and energy poverty index, we used the Handbook on Constructing Composite Indicator - Methodology and User Guide (2008).

composite indicator. We rely on equal weighting. This implies that all dimensions are equally considered in the indicator. Equal weights are often used in the construction of this type of indicator. We assume that a change in one subindicator has the same effect as the others on this composite indicator. Moreover, in this study, a min–max normalised indicator is retained by subtracting the minimum value and dividing by the range of the indicator values. While there are several possible normalisation methods (Freudenberg, 2003, Jacobs et al., 2004), they should be chosen based on data properties as well as the objectives of the composite indicator. Thus, sensitivity analyses are provided in section 4.4 to ensure the robustness of the indicator and the choice of the min–max normalisation.

The three dimensions ($I_{P,i}$; $I_{Q,i}$ and $I_{C,i}$) are justified below.

✓ Household standard of living is captured through $I_{P,i}$

$$I_{P,i} = \frac{P_i - Min(P)}{Max(P) - Min(P)} \quad (2)$$

where P is the ratio between the poverty threshold (60% of the median disposable income after housing and domestic energy cost per consumption unit (PCU)) and household i's disposable income net of housing and domestic energy costs per consumption unit.

This ratio is inspired by the after-energy cost poverty indicator (AFPC), developed by Hills (2011). This approach suggests that households with an equivalized income net of housing and domestic energy costs below the threshold of 60% of equivalized national median income after housing and domestic energy costs are classified as energy poor. This approach successfully identifies households that are in income poverty and whose situation is worsened by energy costs. This approach does not properly reflect the distinct nature of energy poverty but rather provides insights into the broader concept of poverty and, more generally, the standard of living of a household after housing and energy expenditure.

We define household disposable income PCU as total income net of direct taxes, housing costs and energy expenditure:

$$P = \frac{60\%(median\ income - direct\ taxes - domestic\ fuel\ costs - housing\ costs)}{income - direct\ taxes - domestic\ fuel\ costs - housing\ costs} \quad (3)$$

When P increases, $I_{P,i}$ will tend to 1, and then household i will be even poorer.

✓ The indicator of poor housing quality ($I_{Q,i}$).

A household has poor housing quality when it is deprived of basic household utilities and resides in precarious buildings with damp conditions (Charlier et al., 2015; Fondation Abbé-Pierre, 2023). According to the Abbé-Pierre Foundation, living in precarious buildings refers to living in makeshift dwellings or wooden huts. Then, households may live without hot water, electricity, showers or baths. We retain different characteristics of housing quality and attribute scores in sequence. Thus, we define the poor quality of a dwelling (Q_i) as a sum of the different scores of each characteristic and calculate I_q:

$$I_{Q,i} = \frac{Q_i - Min(Q)}{Max(Q) - Min(Q)} \quad (4)$$

where Q_i is the sum of the characteristic scores of household i listed in Table 1. The higher Q_i is, the more precarious the housing is.

Variable	**Value**	**Score**
Dwelling with hot water	Yes, No, No running water	0, 0.5, 1
Quality of wall insulation	Good, Average, Poor	0, 0.5, 1
Quality of electrical installation	Good, Poor	0, 1
Dwelling with showers or baths	Yes, No	0, 1
Living in a makeshift dwelling	No, Yes	0, 1

Table 1 Characteristics of housing quality and associated scores

Source: authors

✓ The indicator of thermal discomfort ($I_{C,i}$)

Finally, we measure thermal (dis)comfort, defined as 'the condition of mind which expresses satisfaction with the thermal environment' (ASHRAE, 2003; ISO 7730, 2005). It describes a person's feeling too hot or too cold. Indeed, studying human thermal comfort is an important issue because it may be related to weather-related mortality among humans (Shalom et al., 2009). Thom (1959) was the first to measure the degree of human thermal discomfort outdoors in the USA by the discomfort index (DI), based on the combination of ambient temperature and relative humidity. High temperature and low relative humidity can aggravate the comfort condition (Md Din et al., 2014), and Thom showed how these factors affect human thermal comfort. To calculate the discomfort index (DI), data related to air temperature and relative humidity are needed. The initial equation of the DI constructed by Thom (1959) is expressed in degrees Fahrenheit with dry-bulb (t_d) and wet-bulb (t_w) temperatures:

$$DI(°F) = 0.4(t_d + t_w) + 15$$

Md Din et al. (2014) attempted to capture the thermal comfort of the population in the cities of Patrujaya and Johar Bahru in Malaysia to determine a thermal discomfort index based on Thom (1959). These cities, which are located in Southeast Asia, are characterised by a tropical climate with high temperatures and relative humidity. Temperatures are between 21.9°C and 32.8°C, and relative humidity is between 82% and 86% (Malaysia Meteorological Department). To measure the impact of those climatic conditions, Md Din et al. (2014) considered a population's thermal perception through a qualitative survey. Md Din et al. (2014) calculated the discomfort index for tropical territories as follows:

$$DI = T - 0.55(1 - 0.01RH)(T - 1.45) \#(5)$$

where T is the air temperature in $°C$ and RH is the relative humidity in %.

Moreover, Md Din et al. (2014) proposed a reading grid for discomfort index interpretation, presented in Table 2.

DI	Interpretation
≤14.9	Uncomfortable
]14.9;19.9]	Comfortable
]19.9;26.4]	Partially comfortable
> 26.4	Uncomfortable

Table 2 Discomfort Index (DI) scale interpretation

Source: Md Din et al. (2014)

This formulation is interesting for our study because it not only provides an indicator of thermal comfort but also allows us to put forward a scale of thermal discomfort due to heat and cold. Moreover, Putrajaya and Johar Bahru have similar weather patterns to the DROM in terms of temperature and relative humidity. Therefore, a household with a very high or a very low value of DI is exposed to thermal discomfort. When we normalise the thermal discomfort indicator of Md Din et al. (2014), we obtain:

$$I_{DI,i} = \frac{DI_i - Min(DI)}{Max(DI) - Min(DI)} \#(6)$$

The closer $I_{DI,i}$ tends to one, the more energy-poor a household will be. The problem is that this normalisation formulation does not allow us to consider cold-related discomfort. This situation is reached when the DI is below 14.9. However, the lower the DI value is, the more $I_{DI,i}$ tends towards zero; i.e., the household in question is not in a situation of energy poverty. To consider both situations of thermal discomfort (when the DI is low for cold discomfort and when the DI is high for hot discomfort), we need to transform the DI parameter. Thermal discomfort situations are of interest in this paper, and the strong point of the indicator is that it can be applied to territories in different climate zones. To transform the Discomfort Index, we first divide DI values into different classes symmetrically (in 2-point steps). Each class is then assigned a value ranging from -6 to -1 for cold discomfort and from 1 to 6 for heat discomfort. The idea is to construct a new scale for interpretation. We call this transformation C (Table 3):

$$C_i = D_i \#(7)$$

DI value *Md Din et al. (2014)*	**Interpretation** *Md Din et al. (2014)*	*Class* *(Authors' new scale)*	**C** *(Authors' new scale)*
≤14.9	Uncomfortable	≤ 5	- 6
		]5;7]	- 5
		]7;9]	- 4
		]9;11]	- 3
		]11;13]	- 2
		]13;14.9]	- 1
]14.9;19.9]	Comfortable		0
]19.9;26.4]	Partially comfortable		0.5
> 26.4	Uncomfortable	]26.4;28.4]	1
		]28.4;30.4]	2
		]30.4;32.4]	3
		]32.4;34.4]	4
		]34.4;36.4]	5
		> 36.4	6

Table 3 Discomfort Index interpretation and transformation

Source: authors

The thermal discomfort is then measured by:

$$I_{C,i} = \frac{|C_i| - Min(C_i)}{Max(C) - Min(C)} \#(8)$$

3.2 Data

Our study uses the 2013 French national housing survey database and ERA5 reanalysis (Copernicus EU) to apply our indicator.

The aim of the French national housing survey database (INSEE, 2013) is to describe housing stock and the conditions of French households' main residences. It is also used to measure the cost of housing. This survey provides highly detailed information about income, costs of energy, housing costs and quality.

The ERA5 reanalysis provides monthly climatic information in terms of temperature, relative humidity, precipitation, etc., across the world in a globally complete and consistent dataset. ERA5 is an open source world database. Therefore, researchers can use our indicator to conduct studies on different territories. The resolution of climatic data can vary from 6 km to 31 km. In this study, we use data with a 31 km horizontal resolution. We can obtain climatic data for Guadeloupe, French Guiana, Reunion Island and Martinique. The outdoor temperature and relative humidity for each household living in a given area can be determined. A description of the main variables used is shown in appendix A.

4 MEASURING ENERGY POVERTY IN THE DROM

4.1 Descriptive statistics

Table 4 presents some descriptive statistics on the three subdimensions of our DEPI indicator.

Variables	Guadeloupe	French Guiana	Martinique	Reunion Island
1. Monetary poverty (means in Euros)				
Income (per cu)	14 559	20 795	20 576	18 785
Direct taxes	855.7	760.1	752	788.3
Domestic energy costs	780.5	918	682	670.4
Housing cost	4 198.4	5 019	4 340	4 634
Disposable income	13 315	14 098	14 802	12 639
2. Housing quality				
Dwelling with hot water				
yes	71.15%	43.00%	65.85%	89.82%
no	28.15%	49.49%	33.62%	10.02%
no running water	0.70	7.51%	0.53%	0.16%
Dwelling with showers or baths				
yes	97.98%	88.89%	96.94%	99.62%
no	2.02%	11.11%	3.06%	0.38%
Quality of wall insulation				
good	49.53%	39.25%	56.51%	54.46%
average	34.22%	42.42%	36.24%	30.10%
poor	12.44%	17.46%	6.99%	14.89%
don't know	3.81%	0.87%	0.26%	0.55%
Safety of electrical installation		82.54%	86.03%	88.89%
good	84.14%	17.46%	13.97%	11.11%
poor	15.86%			
Housing type		71.43%	69.43%	76.46%
detached house	75.89%	20.20%	28.21%	22.71%
apartment in a block of flats	20.61%	1.44%	0.26%	0%
makeshift dwelling	0.15%	6.93%	2.10%	0.53%
others	3.35%			
3. Thermal discomfort				
Temperature (annual means)	21.87°C	23.06°C	22.35°C	23.43°C
Relative humidity (annual means)	81.77%	88.38%	80.48%	88.61%

Table 4 Main descriptive statistics
Source: authors

Average income is higher in French Guiana and Martinique than in Reunion Island and Guadeloupe. Guadeloupe has the lowest annual average income (14,559€), and French Guiana has the highest (20,795€). Domestic energy expenses and housing costs are more important in French

Guiana than in other DROMs, with 918€ of energy expenses per year and 5019€ of housing costs, respectively.

The quality of dwellings in the DROM varies significantly. While almost 100% of the dwellings have running water inside their homes in Reunion Island, Guadeloupe and Martinique, 7.51% of the dwellings in French Guiana do not have access to water in their dwellings. Moreover, in French Guiana, half of the households do not have hot water. Approximately one-third of households do not have hot water in Guadeloupe and Martinique, and only 10% do so in Reunion Island. More than 90% of the dwellings in Reunion Island, Martinique and Guadeloupe have a shower or a bath room inside their houses compared to 88.89% in French Guiana. Wall insulation and electrical installation safety is also of lower quality in French Guiana than in other DROMs. Households live mostly in detached houses in the DROMs. Makeshift dwellings are more widely present in French Guiana than in other islands. It appears that housing quality is better in Reunion Island, Guadeloupe and Martinique than in French Guiana. Reunion Island has the best quality of housing. It has more dwellings with hot water, good wall insulation and safe electrical installations.

Almost all dwellings are equipped with a shower room, and no households live in makeshift dwellings.

Throughout the year, the DROMs enjoy a similar tropical climate. French Guiana is the hottest and wettest territory. Therefore, we expect a higher intensity of energy poverty in this DROM.

4.2 DEPI values for the DROMs

DEPI values for the four French overseas departments are presented in Fig. 2. On average, energy poverty is more intense in French Guiana (0.259) than in other DROMs. More than half of the households have a DEPI value greater than 0.286. In Reunion Island, the indicator is more dispersed, with a mean value of 0.177. We found that 75% of the population has a DEPI value lower than 0.259 in Guadeloupe and 0.237 in Martinique. Energy poverty is less intense in Martinique, with an average DEPI value of 0.11.

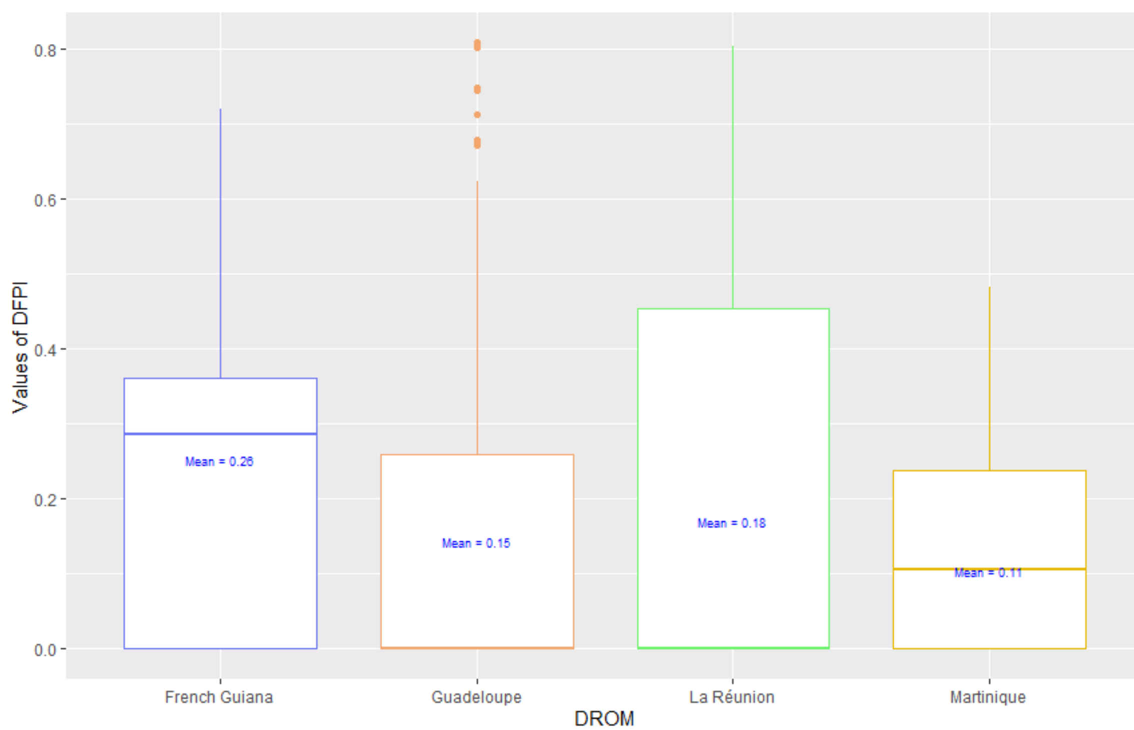

Fig. 2 Distribution of DEPI across the DROMs

Source: authors

Table 5 provides the values of the three dimensions for the DROMs. $\boldsymbol{I_P}$ (expressed as monetary poverty) is 80% lower in Martinique than in other DROMs. After spending on direct taxes, housing and energy, people living in Martinique are the least financially constrained. The average income in this DROM is among the highest, and energy costs are lower than those in other DROMs. The DROM most affected by monetary poverty after housing and energy costs is Reunion Island. Poor housing quality ($\boldsymbol{I_Q}$) is higher in French Guiana (0.1899) than in other departments. It is 13.7% higher than that in Guadeloupe, 21.4% higher than that in Martinique and 44.6% higher than that in Reunion Island. Housing in French Guiana is of lesser quality, as shown previously with statistics. Last, thermal discomfort is important in Reunion Island, where $\boldsymbol{I_C}$ is 0.665 (compared to 0.268 in Guadeloupe, 0.331 in French Guiana and 0.427 in Martinique).

Means value	Guadeloupe	French Guiana	Martinique	Reunion Island
P	-0.089	0.424	1.634	0.05
Q	0.492	0.7597	0.5223	0.3155
C	21.8	23	22.26	23.38
I_p	0.618	0.5824	0.1324	0.7283
I_q	0.164	0.1899	0.1492	0.1052
I_c	0.268	0.3306	0.427	0.6652

Table 5 Dimension values for the DROMs

Source: authors, data ENL 2013 and ERA5 reanalysis

Looking more specifically at the weights of the three dimensions of the indicator helps interpret and compare the intensity of energy poverty in the different DROMs. We can say that if energy poverty is more significant in French Guiana, it is mainly due to the poor quality of the dwellings. On Reunion Island, where the quality of the dwellings is the best, energy poverty is mainly a problem of monetary poverty. In fact, many households are in a situation of income poverty, and housing energy costs exacerbate this poverty. In Martinique, energy poverty exists but is less severe than that in other territories mainly because fewer households are in a situation of monetary poverty. Even if the housing stock on this island is not of good quality, the first dimension (Ip) compensates. Finally, climate discomfort also accentuates energy poverty on Reunion Island, with an Ic higher than that in other DROMs. On Reunion Island, households suffer from hot temperatures on the coast but also suffer from cold temperatures in the mountainous parts of the island. Compared to other overseas departments, Reunion Island has a unique climatic context because it is a mountainous island, with two mountain peaks reaching 3,070 m and 2,632 m and lower temperatures at high altitudes.

4.3 Comparison of the DEPI values with other measures of energy poverty

We want to compare the results of our DEPI indicator with traditional measures of energy poverty. We retain two budgetary approaches, the *10% threshold approach* and the *low income-high cost approach* (LIHC), and two subjective approaches based on households' perceptions of cold and heat inside their houses. The results are presented in Table 6.

DROM	'10% ratio'		LIHC		Cold sensation		Heat sensation	
	Obs	%	Obs	%	Obs	%	Obs	%
Guadeloupe	307	23.93	109	8.49	0	0	56	4.36
French Guiana	219	31.78	88	12.77	0	0	98	14.22
Martinique	272	23.75	91	7.95	0	0	93	8.12
Reunion Island	501	27.45	194	10.63	187	10.25	159	8.71

Table 6 Energy poverty according to budgetary and subjective indicators

Source: authors

Note: Observation (obs) represents the number of households identified as energy poor.

The extent of energy poverty is greater in French Guiana according to the 10% ratio and the LIHC approaches. Similar to the DEPI indicator, the two budgetary approaches also show that the rate of energy poverty is lower in Martinique than in other DROMs. This is in line with what we have shown in the statistics section and in the analysis of the subdimensions of the DEPI indicator above. As monetary poverty is less significant in this territory, fewer households suffer from energy poverty in Martinique.

The subjective cold indicator shows that only households on Reunion Island suffer from cold (10.25%). This appears mainly for households living in the mountainous part of the island (above 800 m altitude). Heat sensation is more important in French Guiana, even if Guadeloupe, French Guiana and Martinique are geographically close. This could be explained by the poor building quality in French Guiana.

4.4 Sensitivity analysis

The construction of the thermal discomfort and energy poverty index (DEPI) is based upon some methodological choices and assumptions. Thus, we conduct a sensitivity analysis to assess the robustness of the DEPI in all three dimensions. We retain two configurations used to test this robustness. First, we assess the sensitivity of the DEPI to extreme values (Tables S2) for each DROM by removing the observations of the populations with the 5% lowest and highest values for each dimension separately. Then, the DEPI sensitivity is also tested according to the poverty threshold (Fig. 3 and Table S3). In fact, we have shown that this first dimension (monetary poverty) plays an important role in the intensity of energy poverty results. Therefore, we will test the results with a poverty threshold of 50% instead of 60%. If the values are quite similar, it supports the choice of equal weights for the three dimensions of the DEPI.

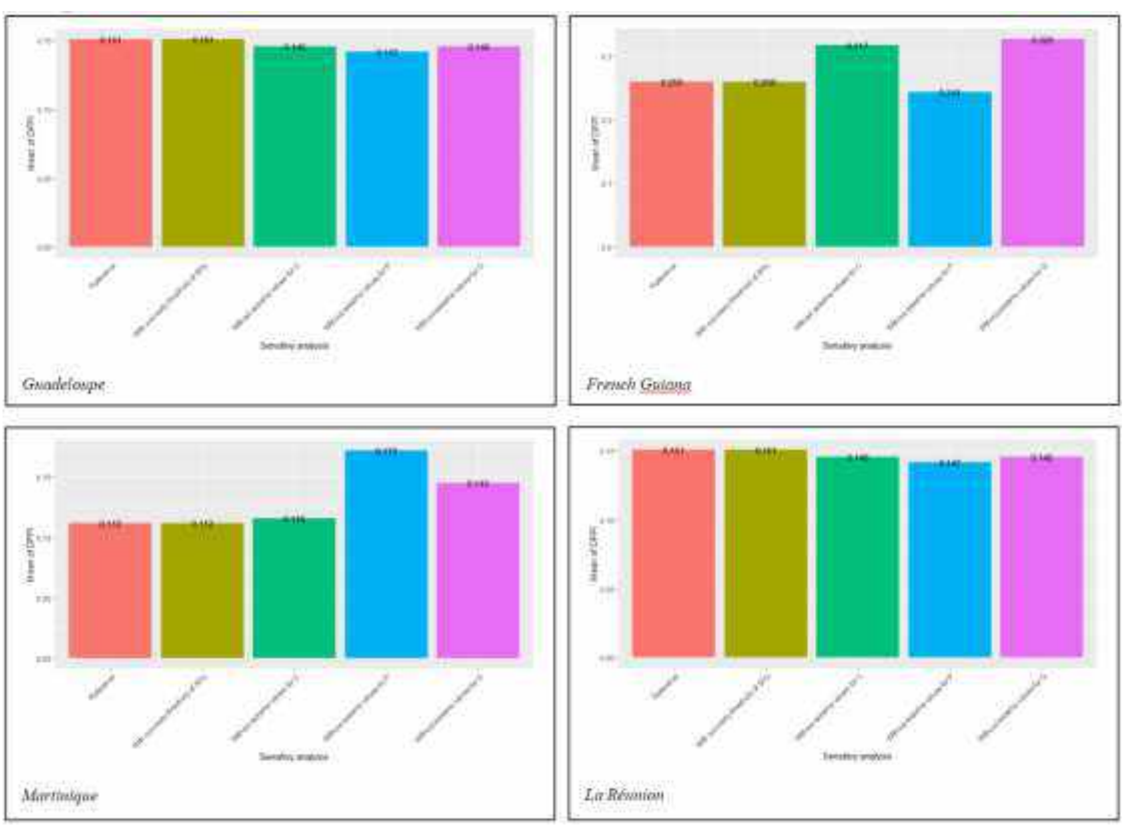

Fig. 3 Distribution of DEPI across the DROMs

Source: authors

The results show that the DEPI values for each DROM are little affected, even though minimum and maximum values are deleted. Furthermore, the DEPI values continue to be approximately 0.151 for Guadeloupe, 0.259 for French Guiana, 0.112 for Martinique and 0.177 for Reunion Island, even when we decrease the reference value of the monetary poverty threshold (from 60% of the median income PCU to 50%). Thus, our methodology to measure energy poverty seems robust.

5 CONCLUSION

Energy poverty is an increasingly serious problem in both temperate and tropical regions. Rising temperatures are exposing increasingly more people to a new form of housing poverty: summer energy poverty. Recent empirical studies have shown that households are no longer able to maintain an acceptable temperature in their homes during heat waves. The consequences on their health can be dramatic (blood circulation problems, worsening of pathologies, dehydration, stress, deterioration of sleep). Several indicators exist to measure energy poverty, but none consider climate dimension in their construction. Moreover, standard measures fail to include several potentially energy-poor households because of their unidimensional aspect.

This study aims to provide a new way to better identify households that suffer the most from energy poverty, whether they are exposed to cold or hot temperature. The thermal discomfort and energy poverty index (DEPI), proposed in this study, is a multidimensional approach to energy poverty based on monetary poverty, building quality and climatic comfort. The originality of the measure was to introduce a climatic dimension in the indicator. We account for climate change by involving exposure to temperature and relative humidity with the calculation of a discomfort index. Higher (or lower) temperatures increase the degree of this exposure and then raise the intensity of energy poverty.

This paper has shown that the DEPI has many advantages. It provides a scale of energy poverty intensity. It helps policy makers target populations with specific policies based on ranges of the DEPI. By enabling calculation of the variance of each dimension for a given territory on a smaller scale (for example, at the neighbourhood level), this index can help policy makers understand which dimension has the highest weight. Then, the geometric mean ensures a certain level of compensability between the three dimensions. If a ‘rich’ household lives in poor-quality housing and in an area with strong thermal discomfort, it can pay for necessary retrofits for the dwelling. Finally, the DEPI can be used to make comparisons among regions or counties, as we did with the French tropical regions. It can also be used to make comparisons over time, for example, to follow the impact of climate change on energy poverty. If the standard of living and the quality of building dimensions do not vary, a change in the intensity of energy poverty could be caused by a variation in the climate dimension of the index. The climatic data ERA5 reanalysis (Copernicus EU) are open source data available all around the world for a long period of time, therefore the DEPI indicator can be easily replicable.

The application of the DEPI to the DROMs have shown that energy poverty is more intense in French Guiana than in other territories due to bad performing insulation housing and weakly present in Martinique. On Reunion Island, where the quality of the dwellings is good, energy poverty is mainly a problem of income poverty as electricity bills exacerbate household’s poverty. Finally, climate discomfort also accentuates energy poverty on Reunion Island, with a higher value of the discomfort index than in other DROMs.

An interesting part of the study would be to analyse energy poverty in a more detailed way in a territory using economic and climatic data on a smaller scale (municipality, or district). Indeed, in areas where there are significant climatic variations, such as Reunion Island, this would make it possible to better characterise energy poverty.

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SUPPLEMENTARY MATERIALS

A Description of used variables

Variables	**Description**
1. Monetary poverty	
Income	*Wage, earned and replacement income, social pensions, interest/dividend/financial income and other incomes*
Direct taxes	*Income taxes*
Domestic energy costs	*Electricity, gas, wood and coal costs*
Housing cost	*Council tax, property tax, loan repayments and condominium charges*

Variables	Description
2. Housing quality	
Dwelling with hot water	*Yes, no or, no running water*
Quality of wall insulation	*Good, average or poor*
Quality of electrical installation	*Good or poor*
Dwelling with showers or baths	*Yes or no*
Housing type	*Detached house, apartment in a block of flats, makeshift dwelling or other*[4]
3. Thermal discomfort	
Temperature	*Outdoor temperature in degrees Celsius*
Relative humidity	*Outdoor relative humidity in %*

Table S1 Description of used variables

B Sensitivity analysis

Percentile of DEPI	Reference	Without extreme values for PCU disposable income	Without extreme values for housing quality	Without extreme values for thermal discomfort	Without extreme values for DEPI
Guadeloupe					
1	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000
6	0.174	0.166	0.174	0.174	0.174
7	0.255	0.239	0.252	0.255	0.251

[4] Other: a separate room, a retirement home, a farm, a hotel room, a nonresidential apartment building

8	0.327	0.301	0.294	0.294	0.260
9	0.469	0.440	0.469	0.431	0.374
10	0.808	0.857	0.808	0.808	0.494
Means	0.151	0.142	0.146	0.146	0.133
French Guiana					
1	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000
3	0.238	0.197	0.299	0.305	0.261
4	0.286	0.258	0.361	0.368	0.315
5	0.286	0.278	0.361	0.368	0.315
6	0.287	0.288	0.361	0.368	0.315
7	0.361	0.320	0.453	0.462	0.391
8	0.397	0.371	0.455	0.464	0.397
9	0.455	0.445	0.571	0.575	0.477
10	0.720	0.807	0.836	0.737	0.573
Means	0.259	0.243	0.326	0.317	0.279
Martinique					
1	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000
5	0.107	0.000	0.142	0.107	0.178
6	0.108	0.179	0.143	0.135	0.180
7	0.171	0.270	0.311	0.235	0.259
8	0.238	0.388	0.315	0.237	0.397
9	0.300	0.486	0.396	0.299	0.445
10	0.483	0.776	0.618	0.466	0.572
Means	0.112	0.172	0.145	0.116	0.172
Reunion Island					
1	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000

5	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000
7	0.442	0.372	0.522	0.442	0.405
8	0.455	0.411	0.537	0.455	0.483
9	0.557	0.487	0.585	0.557	0.526
10	0.804	0.746	0.846	0.804	0.663
Means	0.183	0.154	0.195	0.183	0.169

Table S2 Sensitivity analysis of extreme values

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

	Guadeloupe		French Guiana		Martinique		Reunion Island	
	Reference	New value	Reference	New value	Reference	New value	Reference	New value
P	-0.089	-0.074	0.424	0.354	1.634	1.362	0.050	0.042
$P\ min$	-196.566	-163.797	-691.797	-576.498	-186.794	-155.662	-390.171	-325.143
$P\ max$	121.148	100.956	496.673	413.894	1236.484	1030.404	146.867	122.390
I_p	0.618	0.618	0.582	0.582	0.132	0.132	0.727	0.727
I_q	0.164	0.164	0.190	0.190	0.149	0.149	0.105	0.105
I_c	0.268	0.268	0.331	0.331	0.427	0.427	0.665	0.665
DEPI	0.151	0.151	0.259	0.259	0.112	0.112	0.177	0.177

Table S3 Sensitivity analysis of reference values with a poverty threshold of 50%

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