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Citation for published version:
Soriano-Hernández, P, Mejía-Montero, A & van der Horst, D 2022, 'Characterisation of energy poverty in Mexico using energy justice and econophysics', *Energy for sustainable development*, vol. 71, pp. 200-211. https://doi.org/10.1016/j.esd.2022.09.005

Digital Object Identifier (DOI):
10.1016/j.esd.2022.09.005

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Energy for sustainable development

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OPEN ACCESS

Download date: 24. May. 2025

Energy for Sustainable Development 71 (2022) 200–211

Contents lists available at ScienceDirect

Energy for Sustainable Development

Characterisation of energy poverty in Mexico using energy justice and econophysics

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ARTICLE INFO

Article history:
Received 20 May 2022
Revised 26 July 2022
Accepted 3 September 2022
Available online xxxx

Keywords:
Energy poverty
Energy justice
Econophysics
Mexico

ABSTRACT

The exploitation of limited energy resources can generate socio-economic inequalities calling for a combination of justice with the socio-technical study of modern energy systems to advance its understanding and remediation. Within this context, this paper uses energy justice and econophysics as theoretical and methodological frameworks to discuss issues of energy poverty in Mexico. The results emerging from this research illustrate that, according to data from 2014, around 61 % of Mexican households suffered from energy poverty due to issues of accessibility or affordability of modern energy services and fuels (with 11.54 % of households facing both types of energy poverty). This paper provides a novel approach that combines advanced quantitative methods based on econophysics, with conceptual frameworks from social sciences like energy justice to discuss issues of energy poverty in Mexico. Furthermore, this research performs an approximation to energy consumption in Mexican households based on monetary expenditure, the heat value of fuels and unit prices during 2014. These methods contribute to the understanding and characterisation of household energy needs and energy consumption in Mexico, reducing the existing gap in the academic literature on the analysis and critical thinking of energy poverty in Global South contexts (specifically in Latin America).

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Introduction

Although energy consumption and development are widely seen as interdependent (Goldemberg, 2001; Pasternak, 2001; Dias et al., 2006), the impact of the former on the latter is not the same in all countries, gaining relevance for low and middle-income countries (Martínez & Ebenhack, 2008). Existing inequalities in energy systems can be identified through, for instance, examining the use of various energy resources (Yao et al., 2020) or the distribution of burdens and benefits (Jenkins et al., 2016a, 2016b), regardless of whether their energy systems are operated by the state, private sector or both. The distribution of these energy resources, or their generated wealth, can be explored through the two-class structure of income distribution (Chakrabarti, 2013) or the Gini coefficient corresponding to an exponential function for global energy consumption per capita (Banerjee & Yakovenko, 2010), frequently revealing stable characteristics across different countries.

Over the last decade, energy justice has provided diverse analytical tools and conceptual frameworks to assess the distribution of benefits and burdens from energy systems, allowing researchers to identify the processes behind such misdistribution and recognise the most vulnerable groups (Jenkins et al., 2021). Within this context, frameworks like the three tenets of energy justice (McCauley et al., 2013) and the energy justice principles of availability and affordability (Sovacool & Dworkin, 2015; Sovacool et al., 2016) serve as theoretical and methodological approaches to explore different aspects of issues emerging from energy systems, such as energy poverty.

As a concept, energy poverty emerged mainly from the experience of countries in the Global North, notably the United Kingdom, and has been traditionally constructed by studies focusing on the low-affordability of fuel and heating services (Li et al., 2014; Sovacool, 2015). Nevertheless, it is essential to recognise the contextual understandings of the society in which energy poverty and notions of justice are to be studied and applied, as studies focusing on countries from the Global South can provide different approaches or interpretations of energy poverty (Castán Broto et al., 2018; Monyei et al., 2018). Due to the lack of accurate data on energy consumption and taking into account the contextual importance of energy according to the society

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https://doi.org/10.1016/j.esd.2022.09.005
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in which it is studied, alternative methodologies (compared with the UK origins of this research field) have emerged to study energy consumption related to poverty. These methodologies include Jiang and O'Neill (2004) approach to derive energy consumption from the expenditure on energy services and fuels, and the method suggested by García-Ochoa and Graizbord (2016a, 2016b) to measure energy poverty based on meeting absolute energy needs. Being such a complex societal phenomenon (influenced by age, geography, income, level of education, etc.), it is necessary to use qualitative and quantitative methods and an interdisciplinary approach to capture and discuss energy poverty's complexity (Sovacool et al., 2017; Thomson et al., 2022).

As Thomson et al. (2022) highlight, it is crucial to develop research on energy poverty in countries like Mexico to breach the academic knowledge gap around this phenomenon in regions like Latin America. Especially in Mexico, where academic literature in energy poverty can be reduced to six publications (Ibid.). Against this background, this paper explores the study of energy poverty in Mexico within the theoretical framework of energy justice tenets developed by McCauley et al. (2013) and the principles of availability and affordability initially suggested by Sovacool and Dworkin (2015). In addition to this distinct theoretical framing (elaborated in sections Energy justice and Energy poverty below) and the geographical expansion of energy poverty research in Latin America, this paper provides a methodological contribution by drawing from econophysics to analyse the existing data on energy consumption and socio-economic conditions of Mexican households (further explained in section Econophysics).

Conceptual framing

Energy justice

Guruswamy (2010) coined the term '*energy justice*' as a concept that seeks to combine justice (first virtue of social institutions) with energy (fundamental need and key determinant for human progress). Years later, the term was endowed with its first conceptual frameworks and elements drawn from environmental justice (McCauley et al., 2013). Since then, energy justice has thrived, becoming a recognised and well-developed area of academic scholarship (Jenkins, 2018; Van Veelen et al., 2019), aiming to create a positive impact by influencing energy policy (Jenkins et al., 2016a, 2016b).

According to Heffron and McCauley (2017), the scholarship has three main conceptual frameworks, two of which are relevant to this paper due to their direct implication for the study of energy poverty.

The first framework, proposed by McCauley et al. (2013), considers three tenets of energy justice that address social justice concerns within energy systems: distributional, recognition and procedural justice. Distributive justice calls for the equitable distribution of costs and benefits coming from energy systems among all members of society, regardless of socio-economic status, race, or gender, among others (Jenkins et al., 2016a, 2016b). Recognition justice draws attention to the specific needs, conditions and characteristics of particular social groups, avoiding forms of cultural domination, degradation and devaluation (McCauley et al., 2013), or the distortion in people's opinions that might come across as despicable or degrading (Schlosberg, 2003). Procedural justice concerns access to decision-making processes, calling for fair and equitable processes that involve all stakeholders in a participatory, impartial and non-discriminatory manner to pursue social goals (Jenkins et al., 2016a, 2016b). Therefore, within this framework, energy justice aims to apply these three tenets throughout the energy system (Jenkins et al., 2016a, 2016b). Thus, energy justice serves as a conceptual framework to link energy production and consumption research through the principles of distributional, recognition and procedural justice (Ibid). This integral vision of justice allows us to raise questions about how the different levels of energy needs are recognised and addressed in society (Gillard et al., 2017). Our paper mobilises the three tenet energy justice framework to explore how energy poverty issues in Mexico relate to the dimensions of distributive, procedural and recognition justice.

The second framework of relevance for this work was initially proposed by Sovacool and Dworkin (2015), conceptualising energy justice as a set of eight principles. Although this original framework has slightly changed over time by adding, replacing or modifying different principles (Sovacool et al., 2017), the principles of availability and affordability have remained, being of particular interest for this research. The principle of availability can be understood as the ability of a given energy system to guarantee the provision of sufficient energy resources when needed, encompassing the availability of technological solutions, infrastructure or physical and economic resources in the energy system to ensure energy needs are met (Sovacool & Dworkin, 2015). Under this premise, the principle of availability includes the accessibility to the technologies or devices that enable people to enjoy energy services. Consequently, the deprivation or lack of access to modern energy services, also understood as energy poverty (Sovacool et al., 2016), directly violates the energy principle of availability. This link between the principle of availability and energy poverty through the accessibility or deprivation of energy services is of great relevance for the discussions in this paper. On the other hand, the principle of affordability in energy justice is defined as the right for people, including the poor, to pay no more than 10 % of their income for energy services (Sovacool & Dworkin, 2015; Sovacool et al., 2017). Such definition has a clear link with Boardman's (1991) seminal work, which, as the next section will illustrate, provided one of the first definitions of energy poverty based on an absolute measure to identify fuel poor households.

One of the main limitations of the energy justice frameworks lays in the ambiguity present in some of the definitions and terms (Monyei et al., 2018, 2019). As an example, despite the widespread of energy justice, some authors such as Monyei et al. (2018) argue that its frameworks are not yet complete and that it has failed to provide ample exploration and tangible definitions for concepts like 'sufficient' energy access and mobility. Such ambiguity manifests, for instance, when trying to define the meaning of 'sufficiency' of high-quality energy services for the satisfaction of human needs or financial burdens for consumers, both relevant for the discussions in this paper and related to the principles of availability and affordability.

Energy poverty

Energy is fundamental to providing services like cooking, refrigerating or lighting, as well as efficient and reliable transportation and telecommunication services, among others (Sorrell et al., 2020). Furthermore, lack of access to modern energy services can trap groups, communities and countries in vicious circles of poverty, social instability and underdevelopment (International Energy Agency, 2004). In an effort to avoid such vicious circles, the UN includes access to clean and affordable energy as one of the UN sustainable development goals (SDGs) (UN, 2020). Within this context, the link between energy use and well-being has been increasingly mobilised in development discourses since the beginning of the 20th century with the expansion of the electricity grid in the Global North (Reynolds & Hughes, 1984; Nye, 1999).

As an area of academic interest, energy poverty has been explored extensively over the last decades (Li et al., 2014). Such exploration has happened mainly in the United Kingdom (UK) where the concept of *fuel poverty* emerged during the 1980s (Li et al., 2014; Day et al., 2016). The concept of fuel poverty was coined in response to serious concerns related to heating standards in British households (Ministry of Fuel and Power, 1946; Morris, 1961), in parallel with the oil crisis during the 1970s (Owen, 2010), bringing a strong focus on the affordability of fuels and services (Li et al., 2014; Sovacool, 2015). The concept of fuel poverty evolved to a more widely definition of energy poverty, reaching organisations like the European Commission and the International Energy Agency (EIA) (IEA, 2020; European Commission, 2021).

Although both energy poverty and fuel poverty are descriptors of household energy consumption issues, they are typically used to represent different problems. Energy poverty is generally defined as the lack of access to modern energy services, frequently focusing on countries of the Global South. On the other hand, fuel poverty is mainly used in countries from the Global North (especially the UK) to describe the inability to afford adequate heating services in households (Bouzarovski & Petrova, 2015). Nevertheless, fuel poverty and energy poverty concepts are sometimes used as synonyms to describe issues related to the distribution of energy services, sharing common elements, depending on the geography where households are located and their economy (Li et al., 2014).

Some pioneering works on fuel poverty adopted the so-called '*subsistence approach*', according to which "a household is poor when its income does not cover different basic satisfiers necessary to maintain people's physical efficiency" (Price & Rowntree, 1902). For instance, Lewis (1982) defined fuel poverty as the inability to afford adequate heating in the household, taking the subsistence approach as a reference. Subsequently, the seminal work of Boardman (1991) linked fuel poverty in households to income, proposing a clear definition of a poor fuel home based on fuel expenditure. Under this definition, a fuel poor household is the one which spends >10 % of its income on fuel costs. The relevance of this absolute 10 % expenditure to identifying households facing energy poverty has been mobilised in different studies, especially in the global north (Balaskas et al., 2021; Tundys et al., 2021; Das et al., 2022), but with increasing participation of countries in the global south (Olawumi Israel-Akinbo et al., 2018; Pablo et al., 2019).

Nevertheless, it is essential to recognise that the definition of energy poverty has changed over time. Initially Boardman's 10 % definition of fuel poverty in the UK covered only the cost of heating a space to a particular temperature, typically 21 °C (Boardman, 2012). However, actual expenditure on energy services and fuels can actually vary dramatically if other expenses, such as mobility, are included. It is in such cases that proposals such as Hills' for a context-specific relative definition of energy poverty that considers a combination of household income, household needs and energy costs must be considered and applied. In 2013 Hills (2011, 2012) proposed the 'low-income high cost' measure. Under this new criterion, a household suffers from fuel poverty if its residual income (after fuel costs) falls below the poverty line. This is a relative measure instead of the initial Boardman's definition of 10 % of income spent on fuel (Li et al., 2014). Although often connected, economic poverty does not necessarily lead to energy poverty. For instance, people facing economic poverty might still have access to affordable thermal comfort if they have an energy-efficient home or heating system. In contrast, other economically well-off people might not be able to afford adequate heating without high quality technologies or infrastructure (Bradshaw & Hutton, 1983). Therefore, increasing income can reduce household poverty more broadly without necessarily tackling energy poverty issues (Howden-Chapman et al., 2012). Since energy poverty is a broader concept, even encompassing fuel poverty, some authors have proposed to extend this concept further. For example, Sovacool et al. (2012) suggest that mobility and power should be included as essential energy services. It has also been argued to include the lack of good options to access these services in an affordable, reliable, adequate, quality, safe and environmentally benign manner for economic and human development (Parajuli, 2011).

The energy justice principle of affordability incorporates energy poverty under one of its main conceptual frameworks (Sovacool et al., 2017), making this absolute value of 10 % of household expenditure on energy services a handy tool to identify Mexican households facing energy poverty in this research. Moreover, addressing energy poverty within an energy justice framework could facilitate identifying and remediation of energy injustices across different social strata fairly and inclusively, facilitating the mobilisation of energy justice tenets and principles (McCauley et al., 2013). How energy poverty is measured and vulnerable groups are identified remains a challenge for researchers; it is here where econophysics can shed some light on the matter.

Econophysics

The term econophysics emerged during the 1990s, coined by H. E. Stanley, to characterise the contributions of physics in economics and finance (Mantegna et al., 2000). The kinetic theory of gas collision inspires econophysics literature to suggest alternative mechanisms to the traditional economics that use stochastic processes to describe the variation in individual income/wealth (Kalecki, 1945; Chakravarty & Ghosh, 2009). Thus, econophysics examines the regular patterns observed in the distribution of income (and wealth) as statistical properties arising from the dynamic interaction of various bodies or agents equivalent to the energy transfer resulting from collisions between the atoms of a gas. Such interaction-based models had been suggested and promoted by some statisticians Angle (1986, 2006) and economists (Bennati, 1988) previously. Still, it was not until the 1990s, when econophysics emerged, that these models became widely used (Mantegna et al., 2000).

Econophysics literature argues that the unequal distribution of wealth among individuals or companies can often be analysed following central concepts for thermodynamics and statistical mechanics, such as the Maximum Entropy Principle. Entropy is originally defined in physics as the unavailability of a system's thermal energy for conversion into work, which also relates to the amount of order in a given system (Brissaud, 2005). However, it was not until Shannon's Theory of Information Transmitted through Communication Channels was published that entropy was mobilised to understand socio-technical systems (Shannon, 1948; Montroll, 1981). Within this context, some econophysicists have become involved in the study of energy consumption, recognising the importance of understanding quantitative characterisations of existing inequalities (Banerjee & Yakovenko, 2010; Lawrence et al., 2013). For example, Banerjee and Yakovenko (2010) argue that an exponential distribution can describe the distribution of countries depending on energy consumption per capita, with the number of high energy consumption countries (most in the Global North) decreasing dramatically. It is also argued that inequality in global energy consumption could be closely related to the worldwide redistribution processes of fossil fuels, causing the distribution of global wealth inequity to fit accordingly with this constraint (Lawrence et al., 2013). These examples of econophysics facilitate the elaboration of insights related to the lack of distributive justice comprising the gap in energy consumption between countries in the Global North and the Global South as measured by the Gini coefficient.

Despite the great systemic importance of energy inequality, economists have little research on the extent and evolution of global energy inequality compared to works on income and consumption. Partially inspired by this gap, this work suggests using tools and methods from econophysics to analyse energy poverty and inequality in household energy consumption, discussing the results through the lenses of energy justice.

Methods

Data on income, expenditure and characteristics of Mexican households were analysed using Python programming language version 2.7 and Microsoft Excel version 365. Data was collected from Mexico's National Household Income and Expenditure Survey (ENIGH) and its Module of Socio-economic Conditions, carried out every two years by the National Institute of Statistics and Geography (INEGI, 2015) and published on its website for free and public access. In addition to collecting information on income and expenditure, this survey includes socio-demographic information about households, such as health, education, social security, access to essential services, household appliances, etc.

The available records are only a representative sample of all households in Mexico, including a numerical factor that indicates the number of households they represent on a national scale. Such representativeness means that the results and discussions in this paper must be understood as a useful but speculative modelling of a highly complex Mexican energy poverty landscape. The sample size includes 19,124 households representing 31,128,396 households nationwide (each household record in the sample consists of a weight, indicating the number of households it represents nationally).

The records from INEGI include sufficiently disaggregated data to allow a detailed analysis of the amount, organisation, and distribution of household income and the destination of household expenditures for different goods and services. These records also contain information on the family composition, goods and assets (i.e. refrigerators, automobiles, light bulbs, etc.) held by the surveyed households. The dataset does not include personal information of any kind as INEGI anonymises it, so the privacy of households is not compromised, maintaining their personal and social identities. Finally, the use of household data is for purely academic and non-profit purposes in line with the criteria set out in OECD (2016) research ethics standards. These methods are described in the following sections.

Accessibility of energy services: meeting absolute energy needs

García (2014) points out that the key to understanding energy poverty is to define households' needs and satisfiers through the way energy is used. Therefore, any deprivation of these needs would imply living in energy poverty. Against this background, García created the Meeting of Absolute Energy Needs (MAEN) method taking up Sen's ideas (Sen, 1981) on the complementarity between absolute and relative deprivation. Such an approach implies the differentiation between categories of absolute needs (subsistence, protection, affection, entertainment, participation, leisure, creation, identity and freedom) from existential needs (being, having, doing, interacting) and satisfiers (e.g., shelter, work, privacy, equal rights, language, religion, etcetera) (Max-neef et al., 1992). Since, for Max-neef, Sen and García fundamental human needs are the same in all cultures regardless of the historical and geographical context, they become finite and classifiable. Consequently, it is possible to measure energy poverty through the Household Energy Poverty (HEP) Index. The HEP index measures the lack of ownership of the economic goods or appliances in households listed in Table 1, causing deprivation of energy services for households to satisfy such absolute needs (García, 2014; García-Ochoa & Graizbord, 2016b).

To obtain the HEP index, García identifies six basic energy end-uses for the satisfaction of the absolute, axiological human needs proposed by Max-neef et al. (1992) listed in the fourth column of Table 1[1]. To select economic goods necessary for different final uses of energy, García performed a comparative analysis on each device, its share in the total energy consumption, the percentage of homes that have each device, and the social impact that its deprivation would represent. Thus, if a person or household does not have access to the economic goods or appliances (listed in Table 1), that person or household is considered in energy poverty as it cannot satisfy its human needs through an energy service (García-Ochoa & Graizbord, 2016b). For the case of air-conditioning or ventilation energy end-use, García-Ochoa proposes to take it into account for the HEP index only for households in geographic locations where the average annual temperature is above 26 °C.

Table 1
Selected six key energy services for the Household Energy Poverty Index (HEP). Summary based on García-Ochoa and Graizbord (2016a).

Energy service	Selected economic good	Absolut need satisfied
Food cooking	Gas or electric stove	Subsistence
Food refrigeration	Refrigerator (1998 or later models)	Subsistence and protection
Entertainment	TV or computer with internet access	Entertainment, leisure and creation
Lighting	Incandescent bulb or fluorescent lamp per room in the house	Protection, entertainment, pleasure and creation
Water heating	Water heater or electric/gas stove	Subsistence and protection
Air conditioning or ventilation	A fan for every three people in a household or air conditioning	Subsistence and protection

Once the final energy uses, economic goods and absolute needs have been defined, the HEP index can be constructed assumption a household is living in energy poverty if:

$$\mathrm{HEP}(x_i) < 1 \tag{1}$$

where:

$$\mathrm{HEP}(x_i) = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{2}$$

In these equations x_i corresponds to the different selected economic goods from Table 1. The summation is done up to n depending on the climate where the household is located, as stated by García-Ochoa and Graizbord (2016a): if the household is in a hot climate location, $n = 6$ as it will require ventilation/cooling appliances; otherwise, in temperate climate households, $n = 5$, excluding these appliances. Hence, a household has the selected economic good to satisfy the corresponding absolute need, then $x_i = 1$, otherwise $x_i = 0$. Thus, any lack of an economic good leads to $HEP(x_i) < 1$, meaning that the household would face different degrees of energy poverty.

Approximation of household energy consumption based on their monetary expenditure

The second method used in this work is based on the percentage of income that Mexican households spend on energy services and fuels. This method is based on Boardman's (1991) definition embedded in the energy justice principle of affordability (Sovacool et al., 2017), which states that any household spends 10 % or more of its income on energy and fuel services will be considered energy poor. This method is therefore slightly different from Boardman's initial approach based on an expenditure to satisfy energy needs which vary across geographies or households (for Boardman and the UK the focus was on heating for keeping houses at 21 °C as previously discussed). Additionally, as the definition of energy poverty has been traditionally limited to heating, Sovacool proposed to include expenditure for mobility and mechanical power, broadening the conceptualisation of fuel poverty (Sovacool et al., 2012). Such conceptualisation implies the inclusion of expenditure on gasoline due to the high number of vehicles registered. According to official figures, in 2014, there was a vehicle fleet of >25 million cars in Mexico (INEGI, 2021), approximately one for each five Mexicans or almost one per household (excluding motorcycles, trucks, cargo vans and passenger trucks). This work considers the relevance of such fuel for the Mexican case in contrast to the low figures of expenditure on energy

[1] These end uses were identified by Garcia analyzing information from the 2011 reports of the Ministry of Energy (SENER) and the Institute of Statistics (INEGI) in Mexico. More recently, ECLAC reports show different variations in the percentages of the distribution of energy consumption for final use in the residential sector, with cooking occupying the highest percentage in use and not water heating, as García states in his 2014 paper. This does not exclude the use of the economic goods listed in Table 2 for these energy end-uses.

services focused on household heating due to most temperate climates throughout the territory. On the other hand, the expenditure on public transport would be a very relevant statistic to include as it is captured by the ENIGH data. Other studies related to energy and transport poverty highlight the importance of public transport in understanding energy poverty related to transport (Lowans et al., 2021; Sareen et al., 2022). However, the level of data aggregation of the survey does not allow us to identify relevant information related to its analysis, such as the type of transport, fuel or the percentage of the fare that is directly used in fuel consumption. Solving such lack of data aggregation represents a methodological barrier that scapes to the scope of this study. However, this challenge also represents an opportunity to improve the current state of statistical tools existing in the country. Therefore, we make a call for academics and decision makers to work jointly on addressing this issue to have a better grasp on how energy in transport is used in Mexico.

Additionally, much of Mexico's energy services and fuels are concentrated in cooking and water heating (García-Ochoa & Graizbord, 2016b), either with electricity or with some fossil fuel like liquified petroleum gas. I addition, some households also use some form of biomass (firewood, charcoal) for the same purposes. Although official figures for the use of this type of fuel are debatable (Sánchez-Peña, 2012), the National Forestry Commission in Mexico (CONAFOR, 2013) argues that some rural households could use firewood to satisfy around 80 % of their energy needs. Nevertheless, official figures reported in the ENIGH seem to only include firewood that is purchased, which might underestimate the fact that much of the firewood is collected rather than purchased (Santos González et al., 2012; Silva Aparicio et al., 2018). Consequently, although this work relies on the statistics from ENIGH on purchased firewood, it makes a call to further develop the surveys that facilitate to better quantify energy sources like recollected firewood. The fuels and energy services under consideration for this work are listed in Table 2.

Approximation of household energy consumption based on their monetary expenditure

The methods for measuring energy poverty mentioned so far consider only monetary values (affordability) or accessibility/deprivation of energy services without measuring the amount of energy used at the end of the production chain. Obtaining the amount of end-use energy in households helps deepen the recognition of energy poverty. Thus, we can identify household energy consumption by the level of accessibility/deprivation or expenditure, providing a first approximation to the amount of energy needed to satisfy absolute needs and the required expenditure. Nevertheless, in Mexico, it was not until 2018 that a specific survey was conducted to measure energy use in the residential sector. Such information gap impedes studying the temporal behaviour of energy consumption and expenditure on energy services at the household level. Nevertheless, this work provides an approximation of energy consumption based on the methodology suggested by Jiang and O'Neill (2004), allowing to transform monetary expenditure of fuels and services into energy values considering unit prices and heat values[2] of fuels or services in Mexico for 2014 (See Table 2).

Table 2
Average price and heat values per fuel or energy service in Mexico in 2014.
Sources: Estimations based on (Castillo et al., 2012; CFE, 2014; CONAFOR, 2014; SENER, 2014).

Fuel/service	Average price in 2014 ($/unit)	Heat value
Electricity	0.0036 per GJ	–
Petroleum liquified gas (PLG)	13.762 per kg	0.046 GJ/kg
Natural Gas (NG)	13.94 per GJ	–
Coal	9.8 per kg	0.03 GJ/kg
Firewood	3.2 per kg	0.015 GJ/kg
Oil	13.94 per liter	0.038 GJ/l
87 Octane gasoline	13.31 per liter	0.0311 GJ/l
92 Octane gasoline	14.11 per liter	0.0314 GJ/l

Once the information on prices and calorific values is obtained, energy consumption in households can be calculated from their expenditure on these fuels or services using the following equation,

$$\mathrm{HEC} = \sum_{i=1}^{n} \frac{\mathrm{AFE_i}}{\mathrm{AFP_i}} \times \mathrm{CVF_i} \tag{3}$$

where: *HEC* = Total Household Energy Consumption in Joules.
AFE = expenditure on the ith fuel in monetary values.
AFP = price of the ith fuel in monetary values per unit ($/kg or $/l).
CVF = Heat value of the ith fuel in Joules/kg or Joules/liter.

It is vital to notice that energy values do not consider losses due to the efficiency of appliances nor losses due to the storage, distribution, or transmission of energy. Therefore, the energy per household obtained represent an approximation of the actual energy consumption.

Results

In order to make a comparison between the MAEN method (based on accessibility) and the monetary expenditure method, a filter was applied to use data from households reporting; 1) quarterly expenditure on energy services; 2) responses to questions about the goods considered in the MAEN method; and 3) quarterly income. Such filter meant to reduce the sample to 18,102 households, representing 29,901,931 households in Mexico (96.15 %).

The following sections provide the results obtained for the measurement of energy poverty in Mexico according to the methods previously described. Section Energy poverty by accessibility provides the results from the MAEN methodology related to accessibility of energy services, while section Energy poverty by affordability present the results following the absolute value of 10 % expenditure from total household income related to affordability. Both methods are subsequently used for the identification of households suffering from both types of vulnerabilities in section Mexican households experiencing double energy poverty: vulnerability status based on issues of affordability and accessibility of energy services. Finally, the distributions of household energy expenditure from 2008 to 2014 are shown, and Jiang and O'Neil's methodology is used to estimate household energy consumption during 2014 in section Distribution and inequality of energy monetary expenditure and consumption.

Energy poverty by accessibility

Based on the MAEN method proposed by García-Ochoa and Graizbord (2016a), the HEP index was obtained to measure energy poverty by accessibility. Tables 3 and 4 (below) are developed considering access or deprivation of the economic goods described in Table 1, considering the geographical location of households and the temperature of this location. Table 3 shows the HEP index and the number of households that do not require thermal comfort (fans or air conditioning), while Table 4 contains the cases where households in locations with annual average temperatures above 26 °C, make a requirement of these appliances.

Thus, under the MAEN method, there were 11,613,578 households suffering from different degrees of energy poverty in Mexico, equivalent to 38.84 % of the total national figure of households. These results are closely aligned with those reported by García-Ochoa and Graizbord (2016a, 2016b), meaning only a slight increase in the number of poor households by 1.84 % compared to numbers from 2012 reported by the authors.

[2] The heat value is measured in units of energy/mass or energy/volume and is defined as the amount of heat energy released during the combustion of a specific amount of fuel.

Table 3
Estimated Mexican households in energy poverty in areas where climatic conditions do not require thermal comfort, segmented according to HEP score. The estimated number of households that fall into energy poverty by the MAEN method are highlighted in yellow.

HEP Index	Household	%
0	37,516	0.3
0.2	162,962	1.1
0.4	367,557	2.5
0.6	455,911	3.1
0.8	2,842,711	19.6
1	10,646,465	73.4

Energy poverty by affordability

Under the same conditions as in the measurement of poverty by the MAEN Method, household income and expenditure datasets for 2014 were used. The items of expenditure on energy services and fuels are those considered in Table 2. Therefore, although this method follows Boardman's definition of energy poverty (Boardman, 1991) and the energy justice principle of affordability (Sovacool et al., 2017), our definition includes household expenditure on gasoline (transport in private vehicles), following the ideas of different studies (Robinson & Mattioli, 2020; Martiskainen et al., 2021). Using the criterion of 10 % or more of the income spent on the energy services and fuels listed above, the quotient between expenditure and income is calculated, finding 10,164,200 Mexican households living in energy poverty, representing 34 % of the total Mexican households.

Mexican households experiencing double energy poverty: vulnerability status based on issues of affordability and accessibility of energy services

The similarity in energy poverty figures obtained by the accessibility and affordability principles raises a question related to the distribution of houses facing energy poverty due to issues of affordability, accessibility of energy services, or both. The subsequent application of both the MAEN and the monetary expenditure methods to the same dataset, demonstrates that 3,449,280 Mexican households (11.54 % of total) face energy poverty both through deprivation of energy services and an excessive monetary expenditure on energy services and fuels. Additionally, the average energy consumption at each level of deprivation was approximated using Jiang and O'Neil's methodology. The results are shown in Tables 5 and 6, highlighting in yellow the number of households suffering both types of energy poverty, being the most vulnerable households.

Table 4
Estimated Mexican households in energy poverty in areas where climatic conditions need thermal comfort, segmented according to HEP score. The estimated households that fall into energy poverty by this method are highlighted in yellow.

HEP Index	Household	%
0	57,526	0.4
0.17	456,055	3.0
0.33	662,488	4.3
0.5	766,663	5.0
0.67	1,315,700	8.5
0.83	4,488,489	29.2
1	7,641,888	49.7

The results highlight that energy poverty due to monetary expenditure occurs at all levels of deprivation of accessibility to energy services. Moreover, vulnerability related to monetary expenditure occurs in households without any issues of accessibility (HEP index equal to 1), adding up to 6.7 million households in both tables. The data also shows some counter intuitive results such as, the average amount of energy being used per household being lower at HEP = 0.2 (0.17 for households requiring thermal comfort) than HEP = 0 (households with a higher level of energy poverty by accessibility). Even households at HEP = 0 (that do not require thermal comfort) consume more energy on average than households with HEP = 0.4. These results might be considered contradictory, since households at level 0 lack all the services covered by the MAEN method. A possible explanation for this is that households at level 0 use a higher amount of 'dirty' and inefficient fuels with high heat values, such as firewood, coal, or oil than households within the next highest index. Finally, it could be striking that the households in greatest energy poverty due to deprivation that do not require thermal comfort (HEP = 0, 0.2 and 0.4) spend on average >10 % of their income on energy services and fuels. However, this result is reversed in households that require thermal comfort, with the lowest levels of energy poverty (HEP = 0.83 and 1) spending, on average, >10 % of their income on energy services. These results in combination with the high average quarterly energy consumption could suggest that households experiencing lower levels of energy poverty due to deprivation are more energy-dependent, making them more likely to suffer energy poverty due to monetary expenditure.

Distribution and inequality of energy monetary expenditure and consumption

The distribution of monetary expenditure on energy services is relevant for characterising energy poverty by affordability and thus, identifying vulnerable groups. Fig. 1 shows histograms of monetary expenditure on energy by Mexican households over ten years. As a first impression, this figure shows the high left skewness of the data, leading to a logarithmic analysis of the data to reduce its dispersion around its mean and avoid working with a heavy tail in the data.

After applying a logarithm to the data for each period and normalising the histogram, some statistical properties of the data emerge. First, it is possible to appreciate the stability of the distribution of monetary expenditure over time. Fig. 2 shows that except for some deviations, the histograms of monetary expenditure remain more or less stable around a mean value ranging between 50 and 400 USD (between 4 and 6 on the X-axis in Fig. 2 on the logarithmic scale). Secondly, as these distributions are stable around a mean point, it is possible to recognise normality in the log-log scale monetary expenditure energy data. Fitting these data to a Normal Distribution (red curve in Fig. 2) on this scale yields correlation coefficients between the data and this theoretical curve >0.9 in almost all years (the remaining relevant parameters of these distributions are shown in Table 7). This implies that a log-normal distribution would adequately fit the shape of the data on a linear scale. The implications of such stability in the distribution of monetary expenditure are briefly addressed in the next section.

Table 7 notes the slight change in the average logarithm of expenditure μ since 2010 and the constancy of the standard deviation σ throughout the whole period. The quasi-stability of these parameters is an indication that, despite variations (primarily increases) in the prices of energy services and fuels, there are no drastic changes in the behaviour of consumers of these services and products, and, overall, Mexican households maintained their energy consumption patterns. This same table shows the Gini G coefficient for expenditure on energy services and fuels, showing that inequality in energy

Table 5
Key indicators of households that do not require thermal comfort by deprivation level. Households experiencing energy poverty by affordability and by accessibility are highlighted in yellow.

HEP Index	0	0.2	0.4	0.6	0.8	1
Households	37,516	162,962	367,557	455,911	2,842,711	10,646,465
Households spending >10% of income in energy	12,572	33,125	60,767	108,460	922,447	3,341,658
Average expenditure (% of total income)	10.52%	10.01%	16.31%	9.02%	9.40%	9.51%
Average quarterly energy consumption (GJ)	2.81	1.34	2.38	4.04	5.58	8.53
Total households	14,513,122					

expenditure has an upward trend in 2008–2012, then dropping back a bit and stabilising just below 0.56.

Measuring energy poverty at three different levels of expenditure (below 31 USD, between 31 USD and 366.5 USD, and above 366.5 USD) levels of the distribution in Fig. 4 during 2014 yields noteworthy results, shown in Table 8. Although these results will be discussed in the next section, it is essential to highlight how all expenditure levels show levels of energy poverty either in terms of affordability or accessibility.

A graphical representation of inequality using the Lorenz curves is shown in Fig. 3. Note the increase in the area under the ideal curve in blue, indicating a gradual increase in inequality in monetary energy consumption.

The last plot presented is the complementary cumulative distribution function (CCDF) of household energy consumption obtained using Jiang and O'Neil's method (Fig. 4). This adjustment was made in line with the trend in econophysics of two different distributions. Most of the households (98 %) seem to follow an exponential distribution (red curve), while a minority (2 %) seem to be well fitted by a Pareto distribution (green curve), similar to income distribution. This behaviour is similar to the one described by Yakovenko for the distribution of energy consumption per capita worldwide (Lawrence et al., 2013). The meaning behind the duality of the distribution of energy consumption will be briefly addressed in the next section.

Discussion

The study of energy poverty in Mexico and other Latin American countries remains a persistent gap in the existing academic literature (Thomson et al., 2022). Sheinbaum et al. (1996) argued that during the 1970s, 1980s and 1990s, the number of individuals per household was regarded as a more important factor for measuring energy consumption than income or prices. Other studies (Sánchez-Peña, 2012; Franco & Velázquez, 2016) have already shown the importance of socio-demographic factors in energy consumption for Mexican households, based on Jiang and O'Neill (2004) methodology. However, none of these works measured the number of households in energy poverty conditions. It was not until Garcia's works (García, 2014; García-Ochoa & Graizbord, 2016b), that other few studies in Mexico (six including the work of Garcia-Ochoa) continued with this effort (Thomson et al., 2022). Therefore, this paper contributes to the exploration of energy poverty in Mexico and Latin American countries through the use of statistics and econophysics as secondary data analysis, framed in the energy justice tenets. In the following sections, we discuss this novel contribution to the measurement of energy poverty for the case study of Mexico, also elaborating on how the results from this research contribute to theorisations of energy justice and energy poverty.

Energy justice as distribution and recognition: identifying types and levels of energy poverty in Mexico

Regarding distributional justice, the individual application of MAEN and monetary expenditure methods in 2014 expenditure data allows for an account of the distribution of energy poverty burdens in Mexican households based on their socio-economic and geographic features. Particularly, the MAEN method enables the identification of households suffering from energy poverty due to a lack of access to modern energy services, thus preventing households from satisfying their absolute energy needs. The most prevalent final energy uses among Mexican households are cooking, water heating, lighting, and entertainment. On the other hand, Boardman's method accounts for the number of households suffering from energy poverty due to a high percentage of income spent on energy and fuel services. The most significant expenditures are gasoline, electricity, and liquefied petroleum gas (LPG). The similarity of the distributional figures obtained by each method raises the question of whether the same households suffering from energy poverty due to deprivation of energy services (issues of accessibility) also suffered from excessive monetary expenditure (issues of affordability). The results presented in this work allowed to open an even deeper discussion grounded on the subsequent application of both methods in combination, leading the discussion toward the tenet of recognition.

First, it was possible to identify the most energy-vulnerable group. These households experience what might be defined as double or overlapping energy poverty since they require a high monetary expenditure to pay for energy services, and yet they do not have all the necessary

Table 6
Key indicators of households that require thermal comfort by deprivation level. Households experiencing energy poverty by affordability and by accessibility are highlighted in yellow.

HEP Index	0	0.17	0.33	0.5	0.67	0.83	1
Households	57,526	456,055	662,488	766,663	1,315,700	4,488,489	7,641,888
Households spending >10% of income in energy	12,258	68,027	99,880	151,273	388,727	1,591,744	3,373,262
Average expenditure (% of total income)	7.87%	6.28%	6.47%	7.92%	8.28%	10.26%	12.11%
Average quarterly energy consumption (GJ)	1.45	1.32	1.62	2.61	4.26	6.73	11.08
Total households	15,388,809						

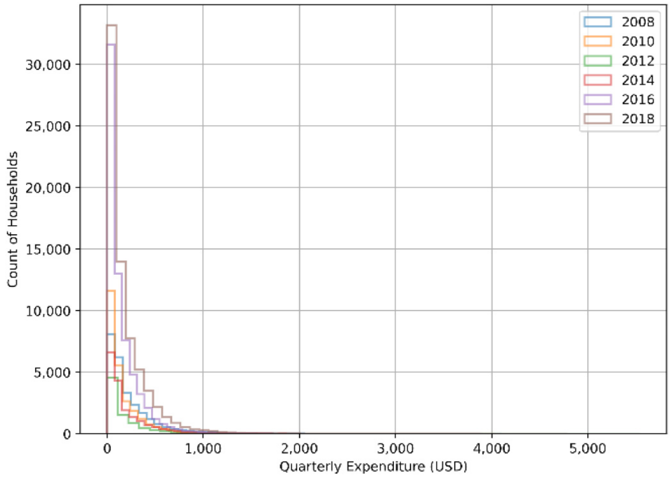

Fig. 1. Histograms representing the distribution of monetary expenditure on energy services and fuels by Mexican households from 2008 to 2018.

satisfiers to meet their energy needs. Even if the distributive figures representing a solution for applying both methodologies individually lead to similar figures of energy poverty in Mexico, in isolation, they miss-recognise this most vulnerable group. Slightly >1 in 10 Mexican households live in this situation. Two out of three of these most energy-vulnerable households are in states with hot climates, which means they require thermal comfort. The recognition of these households by their geographical location and type of population, and their consumption habits for the satisfaction of their absolute energy needs should allow the implementation of concrete strategies targeted to minimise their energy vulnerability. Lack of recognition or misrecognition of these households could condemn them to a vicious circle of poverty from which they will not be able to escape, affecting other aspects of the household such as education or health. The satisfaction of the absolute energy needs of households at the worst level of energy poverty by deprivation is compromised or unsatisfied by modern energy services, forcing them to use 'dirty' fuels as substitutes, especially for cooking or heating. Despite the relatively small number of households experiencing double or overlapping energy poverty, it is vital to recognise them as the most vulnerable groups in the situation of energy poverty.

The results obtained from the different methods used in this work allow us to recognise the complexity of the energy poverty problem in

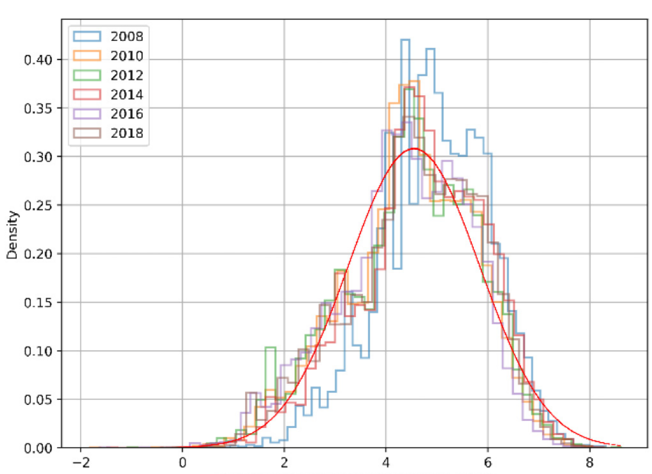

Fig. 2. Normalised histograms of monetary expenditure on energy services and fuels in logarithmic scale and normal curve fit.

Table 7
Parameters of the log-normal distributions that best fit the data: average of logarithm of expenditure μ, standard deviation σ, and correlation coefficient ρ^2, Gini index **G** and entropy **H** for the 2008–2018 period.

Year	<μ>	σ	ρ^2	Gini (G)
2008	4.942	1.088	0.912	0.519
2010	4.448	1.259	0.914	0.565
2012	4.456	1.324	0.892	0.581
2014	4.679	1.249	0.919	0.559
2016	4.345	1.270	0.915	0.556
2018	4.547	1.292	0.902	0.558

the country. Thus, although the importance of economic, geographical and behavioural factors for the satisfaction of energy needs was recognised, it would be interesting to evaluate the role that other factors have in energy decision-making, such as education, type of employment or gender. Furthermore, considering geographic information systems (GIS) to explore energy poverty in Mexico would further enrich the MAEN method, which already considers the average annual temperature of the state where the household is located. The use of GIS tools would also allow a much more precise characterisation of energy poverty in Mexico, as Chatterton et al. (2016) demonstrated with machine learning algorithms implemented to find common patterns (clusters) among socio-demographic, geographic and economic data of households in the UK. Poruschi and Ambrey (2018) also used these methods to illustrate how a higher urban density corresponds to a higher probability of experiencing fuel poverty in Australia. Hence, this work opens the debate to implement this type of technique in socio-demographic, geographic and economic data to make a punctual characterisation of energy poverty in Mexico.

Multicausal energy poverty in Mexico: energy poverty by accessibility and affordability

This paper suggests that, in Mexico, having a high level of monetary expenditure, it is more likely to suffer from energy poverty by affordability, as households require >10 % of their income to pay for energy and fuel services. At the other extreme, the situation is reversed, with fewer households using >10 % of their income to pay for energy and fuel services. However, when measuring the capacity to meet their basic energy needs, most of these households suffer from energy poverty, which means that in this region of the distribution monetary expenditure is not a determinant factor of their vulnerability.

Another interesting result is that the low affordability of energy services and fuels permeates all levels of energy poverty by deprivation or the energy principle of availability. This result is not minor and highlights the multicausal nature of energy poverty in Mexico. As the level of poverty due to incapability of meeting absolute energy needs decreases, the percentage of households spending >10 % of their income on energy by level of deprivation stagnates at around 26 %. Such results suggest that in the group of households located in hot climates (i.e., requiring thermal comfort), up to 44 % of households that do not suffer from energy poverty due to deprivation do live in energy poverty due to monetary expenditure. In other

Table 8
Energy poverty figures at different expenditure levels.

Energy poor by (% of total households)	Level of expenditures		
	Expenditure < 31 USD	31 USD ≤ expenditure ≤ 366.5 USD	366.5 USD < expenditure
Total households	16.1 %	67.4 %	16.5 %
Affordability	0.4 %	22.6 %	11.0 %
Accessibility	10.8 %	25 %	3.1 %
% of total residential energy consumed	1.4 %	48.6 %	50.0 %
Average income spent on energy (%)	2.7 %	10.3 %	17.0 %

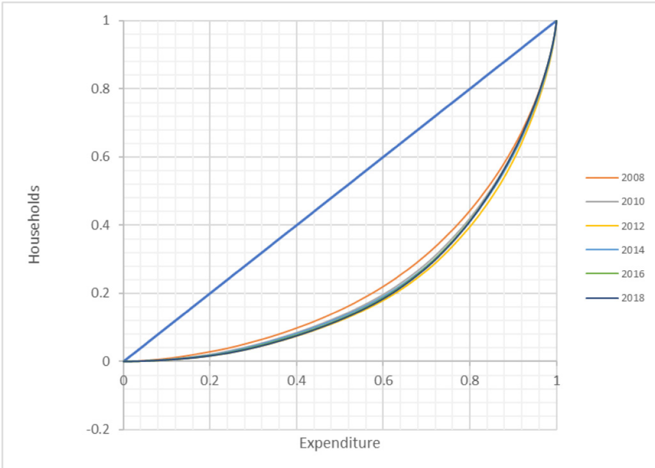

Fig. 3. Lorenz curves of expenditure in energy for each year from 2008 to 2018. Note the shift to the right in the curves, increasing the area and, therefore, the estimates of inequality.

words, it seems that in Mexico access to the goods needed to satisfy absolute energy needs (avoiding energy poverty by issues of accessibility) causes some households to acquire new levels of expenses that make them fall into energy poverty by expenditure. This phenomenon may be explained because as levels of deprivation are overcome, new needs such as mobility begin to be acquired, and with it, the purchase of motor vehicles or even larger and more energy-consuming household appliances. This compromises the economic stability of households, as their income may not be sufficient to maintain the new levels of consumption acquired, thus falling into energy poverty by expenditure.

Conversely, up to 34.5 % of households that meet none of their absolute energy needs (HEP = 0, households not requiring thermal comfort) also suffer from energy poverty due to affordability (see the second column of Table 3). The most significant expenditure in these households is on firewood and gasoline, without full consideration of potential costs associated with variables like time spent by people in recollecting

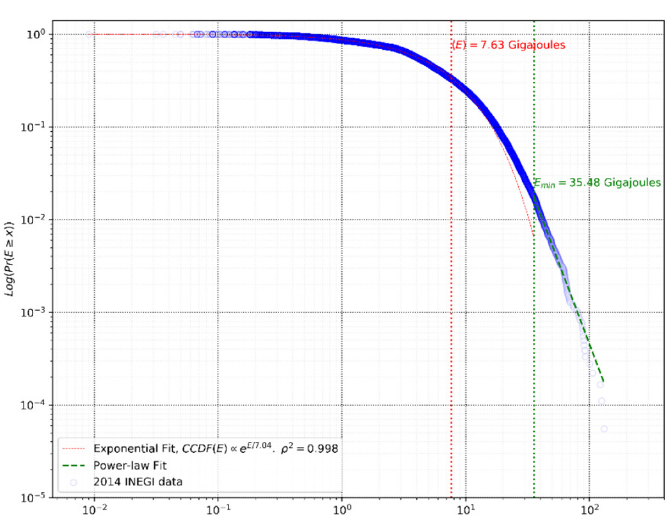

Fig. 4. CCDF of household energy consumption during 2014, built on Jiang and O'Neil's methodology. Notice the dual behaviour of the distribution, fitted with exponential distribution for the bulk of the data (red dotted curve) and power-law for the highest values (green curve). The minimum value from which the power-law begins E_{min} is shown in green.

wood (Santos González et al., 2012) which its outside of the scope of this work. Therefore, it could be concluded that most households in Mexico (around 61 %) suffer from at least one type of energy poverty (access or affordability), and in the worst case, from a combination of both (11.54 % of households). Therefore, only a little <4 out of 10 households in Mexico are free from suffering any kind of energy poverty. Thus, in Mexico, the issue of energy poverty mutates from an issue of accessibility to modern energy services to a problem of affordability of these required services, with most households suffering any of these two types of energy poverty in 2014.

This transition from energy poverty by accessibility to energy poverty by affordability could be explained by different aspects that force households to change their consumption habits. Households that have already met most or all their absolute energy needs are likely to seek to meet a new satisfier, such as mobility, as suggested by Sovacool et al. (2012). This new satisfier generates a new consumption habit, as is the use of gasoline for motor vehicles or the acquisition of a cooling system. Consideration of this new satisfier would create new methodological issues. The main variable would be the inclusion of motor vehicles in the HEP index for satisfying the fundamental axiological need of subsistence, protection, or even leisure and entertainment. Although arguably, not all households require a private vehicle for the displacement of their members, they do require meeting their mobility or transportation needs differently. Therefore, the index may consider either the ownership of a vehicle or the possibility of using public transportation for their displacement. This addition, in turn, forces an increase in the consideration of a 10 % of income spent on energy services and fuels as an absolute value for the energy poverty line. Alternatively, Hills' relative approximation based on a poverty threshold and the residual income after monetary expenditure on energy may be considered to contextualise energy poverty in Mexico (Hills, 2011, 2012). Such recognition of public transport as a relevant element of energy poverty, along with the methodological challenges to access sufficiently disaggregated data for the accurate measurement of energy in public transport comprise a clear gap for future research.

The inclusion of energy consumption as a function of monetary expenditure at each poverty level highlights the importance of the relationship between these indicators. As energy poverty by deprivation is reduced, the amount of energy used by households increases. Thus, consumption habits are altered as modern energy services become accessible and more money is available to pay for them. More access implies more energy use and monetary expenditure, with one notable exception. By the MAEN method, it was possible to identify for 2014 that households that do not meet any of their fundamental energy needs consume more energy on average than households that meet only one need (see Tables 5 and 6). Moreover, in the case of not requiring thermal comfort, homes that do not satisfy any need even consume more energy on average than homes that meet two absolute needs. The simplest explanation for this is the small number of households with a HEP = 0 compared to households in the two higher levels (HEP index of 0.2 and 0.4). Also, the total amount of energy consumed at this lower level is relatively comparable to the consumption at higher levels, although with significant inputs of "dirty" fuels such as firewood, oil or LPG and relatively low electricity consumption. A similar explanation can be provided for this higher energy consumption of the lower deprivation level in households that do require thermal comfort.

Based on Sen's (1981) work on the irreducible core of absolute deprivation and Max-Neef et al. fundamental needs (Max-neef et al., 1992), the MAEN method can be the starting point for the calculation of a 'sufficient' value of energy consumption in Mexican households. This value would work as a guide to estimate a minimum value of energy that meets the absolute energy needs considering the satisfiers raised by García-Ochoa and Graizbord (2016a) by estimating their energy use and probably with additional energy uses such as mobility. The 'sufficient' energy value, in addition to functioning as a strategy to reduce energy consumption in households with low levels of deprivation measured by the MAEN method, could be considered a guide to estimate a minimum 'fair' consumption in households with the highest levels of deprivation. Such fair minimum consumption must enable households to exercise their energy rights, thus promoting proper and adequate social development (Sovacool & Dworkin, 2015; Thomas et al., 2019; Sorrell et al., 2020). Furthermore, the value must be obtained by considering the most efficient and least polluting energy services and fuels to promote the sustainable use of energy. However, it would not be fair to limit the usage of 'dirty' fuels if households do not have access to modern energy services to avoid the energy 'bullying' raised by Monyei et al. (2018) (on a domestic scale). Nevertheless, it is also essential to consider that such 'fair' consumption value will be different across different households where individuals have unique energy needs (Snell et al., 2015) or across locations with different climates (García-Ochoa & Graizbord, 2016b). Exploring the usefulness of finding and proposing these fair values and translating them into policy that aims to ensure a fair and equitable energy basis could be an important research topic for future work.

Econophysics enriching energy poverty and energy justice debates

Up to this point, the indicators and tools proposed in this work allow the identification and recognition of the different groups formed when contemplating the different ways of defining energy poverty. The tools used in this work have allowed us to dive in the empirical study of energy poverty and possible theoretical mechanisms that explain the global behaviour of this phenomenon.

The stability of the distribution of monetary expenditure over ten years is remarkable (Fig. 1), being fairly fitted by the log-normal distribution function every year. The only significant variation is in the average logarithm of expenditure μ (see Table 7), which increases from 2010, just after an abrupt fall during the 2008 crisis. The variation of μ in a 10-year period reflects the changes in the purchase cost of fuels and energy services. However, it is notable that the dispersion σ in this period has hardly changed. The average value of σ is 1.247 with $\langle(\sigma-\overline{\sigma})^2\rangle^{1/2}=0.075$ (standard deviation of the very same standard deviation values). The largest variation from the average σ is 1.088 in 2008, just after the financial crisis as previously mentioned. The Weber-Fechner law could give a possible explanation for the stability of the standard deviation in this period. In short, this law tells us that the slightest discriminable change in the magnitude of a stimulus is proportional to the magnitude of the stimulus itself. Therefore, and in analogy to the argument used by Montroll (1981), the consumption of energy services and fuels is independent of the variation of prices since these usually cannot be replaced and are necessary to satisfy the absolute energy needs shaped by their habitual behaviours, as suggested by García.

In other words, as long as the energy system organises to keep the spread of prices in a 'reasonable' range, people may not notice (or care for) these variations, stagnating both the spread σ and average μ of the logarithm of monetary expenditure. Furthermore, the increase in the price of certain energy services or fuels due to inflation will be balanced with the reduction of others due to, for example, technological improvements, keeping the dispersion of monetary expenditure on energy constant. Similar results had already been documented in Mexico by Sheinbaum et al. (1996) from the 1970s to 1990. These results show that the strategy followed by each household to meet their absolute energy needs will not have a strong influence on the overall behaviour of the probability distribution of monetary expenditure. Thus, if the log-normal distribution well represents the distribution of expenditure, it could be argued that the energy system itself would be self-organising to ensure energy services and fuels continue to be consumed, even if this means restricting the average expenditure and its dispersion. Hence, complex issues such as energy poverty at the household level could be modelled and analysed with relatively statistical simplicity over time, allowing relevant discussions and potential solutions to emerge. It is expected that the use of maximum entropy methods, along with the proper integration of a case study social context, can serve to develop appropriate contextualised solutions for the eradication of energy poverty.

Finally, the cumulative complementary distribution shown in Fig. 4 shows a somewhat different behaviour than the other graphs. This result is relevant as it opens the debate on the origin of this two-class structure in energy consumption. Indeed, the volume of data used in this work is larger than the available data on the study energy consumption per capita worldwide used by Banerjee and Yakovenko (2010), where the simple exponential distribution seems to fit all the range of energy consumption, so it is more likely to have larger deviations from the exponential behaviour. However, it is also possible that the exponential function as equilibrium distribution does not hold for the entire range of domestic energy consumption. Semieniuk and Weber (2020) predicts the absence of statistical equilibrium in data sets that consider multiple reasonable methods to add up heterogeneous energy carriers (coal, oil, electricity, etcetera), which might hold for domestic energy consumption in Mexico during 2014. The consideration of several types of these carriers in the domestic consumption seems to show that although about 99 % of the households in Mexico seem to be in statistical equilibrium during this year (exponential distribution), there is at least 1 % that is far from this equilibrium in the high energy consumption range following a power-law distribution instead. This result opens the debate to consider the entire energy production chain in subsequent work to characterise energy consumption among individuals or households better. The stability on energy consumption could be inferred from the constancy in the distribution of monetary consumption in energy services and fuels over the last ten years. However, due to the dependence of Jiang and O'Neil's method on unit prices of services and fuels, yearly variations in these values could lead to different results in final energy consumption. Therefore, it is suggested to make an exhaustive investigation on the unit prices for more years to have more precise results when obtaining the probability distributions.

Conclusions

This work demonstrates the usability of econophysics as a conceptual and analytical tool to examine energy poverty. When linked to the conceptual framework of energy justice, econophysics provides a tool to identify the levels and types of energy poverty experienced in Mexico based on the distribution and recognition tenets. Relying also on concepts and methods that emerged within the same field of study of energy poverty, it was possible to characterise this phenomenon using 2014 data with precision.

Firstly, this work demonstrates that Mexican households suffer from poverty due to issues of accessibility of modern energy services and low affordability of these services and fuels. The application of two methods arising from different approaches to energy poverty allows for recognising the most vulnerable households in this country. Thus, it was possible to identify that during 2014 around 6 out of 10 households (61.3 %) faced energy poverty. 38.84 % of Mexican households suffered from accessibility issues impeding meeting their absolute energy needs, 34 % faced a high economic burden while purchasing energy services and fuels, and about 11.54 % of Mexican households simultaneously suffered both situations. These results demonstrate the multicausal origin of energy poverty in Mexico. As energy poverty by issues of accessibility to energy services (energy justice principle of availability) is overcame, some households start suffering from energy poverty by monetary expenditure (energy justice principle of affordability).

Secondly, this study shows that households have a significant monetary expenditure on gasolines in Mexico. Therefore, this study demonstrates the need to consider the transportation of household members as a core element when debating or calculating energy poverty in future studies. This argument is confirmed by the possession, on average, of almost one car per household in Mexico, so ignoring the mobility needs of household members means excluding the satisfaction of an essential absolute energy need. However, the inclusion of this new need would represent a considerable methodological challenge for the MAEN method. Furthermore, it would force the monetary expenditure method to either increase the 10 % threshold or use a relative definition of energy poverty by expenditure, as proposed by Hills (2011, 2012). Such recognition of transport for Mexican energy poverty also comprises a call for future research that challenges traditional conceptualisations of what are energy needs, and advance the understanding of energy poverty in traditionally overlooked regions like Latin America (Thomson et al., 2022).

Thirdly, the use of advanced quantitative methods and tools such as those proposed by econophysics might enrich the field of energy poverty and justice. These tools are helpful for an in-depth study that better identifies vulnerable groups and the burdens that lie on them. Nevertheless, this work also joins the call for strengthening the use of qualitative methods in energy poverty studies. We believe such an approach would allow us to better navigate the nuances required for developing new conceptualisations and understandings that are both inclusive and context-sensitive for countries in the global south, like Mexico. The methodology used for this study excludes the energy efficiency of the goods and appliances considered, which reduces the precision of the energy values obtained by the Jiang and O'Neil method. The quantitative analysis developed in this work also highlights the need for academics and decision makers to jointly improve statistical tools and energy related surveys, facilitating to capture relevant or more disaggregated information (i.e. collected firewood or public transport) necessary for an in-depth understanding of energy poverty in Mexico. Additionally, the work could also be improved or complemented by qualitative methods, such as surveys to know households perceptions and provide a deeper understanding of their energy consumption habits. In addition, this type of survey would help know if households themselves are aware of their energy vulnerability condition, which would allow generating awareness campaigns in the country on energy use. The most recent surveys carried out by INEGI on energy consumption seem to include some questions along these lines, although they do not delve into the feelings that the members have about their energy condition.

This work contributes to the efforts of opening new venues for studying energy poverty in countries of the Global South, such as Mexico, broadening the criteria established in this work. For example, applying the MAEN method to characterise energy poverty depends on the location of households in rural or urban areas. Including geographical information systems (GIS) that allow more precise mapping of the climatic conditions of the areas under study in analogy to Chatterton et al. (2016) could refine the MAEN method. Therefore, the MAEN method should be adapted to include the need for mobility and precise GIS data to improve the results shown in this work. There is still a lot of ground to cover in studying energy poverty in Mexico. This work aims to contribute to the recognition of the most energy-vulnerable households and advance toward the procedural principle of energy justice (through policy and decision making) to alleviate their vulnerability. Thus, this work is expected to motivate future projects related to decision-making processes that make Mexican households' energy consumption more equitable, in a safe and sustainable manner.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Angle, J. (1986). The surplus theory of social stratification and the size distribution of personal wealth. *Social Forces*. https://doi.org/10.1093/sf/65.2.293.

Angle, J. (2006). The inequality process as a wealth maximizing process. *Physica A: Statistical Mechanics and its Applications.*. https://doi.org/10.1016/j.physa.2005.11.017.

Balaskas, A., et al. (2021). Energy poverty in the mountainous town of Metsovo, Greece. *Journal of Mountain Science*, *18*(9), 2240–2254. https://doi.org/10.1007/s11629-020-6436-1.

Banerjee, A., & Yakovenko, V. M. (2010). Universal patterns of inequality. *New Journal of Physics.*. https://doi.org/10.1088/1367-2630/12/7/075032.

Bennati, E. (1988). *La simulazione statistica nell'analisi della distribuzione del reddito: modelli realistici e metodo di Monte Carlo.* Pisa: ETS Editrice.

Boardman, B. (1991). *Fuel poverty: From cold homes to affordable warmth.* London, United Kingdom: Belhaven Press.

Boardman, B. (2012). Fuel poverty synthesis: Lessons learnt, actions needed. *Energy Policy*, *49*, 143–148. https://doi.org/10.1016/j.enpol.2012.02.035.

Bouzarovski, S., & Petrova, S. (2015). A global perspective on domestic energy deprivation: Overcoming the energy poverty-fuel poverty binary. *Energy Research and Social Science*, *10*, 31–40. https://doi.org/10.1016/j.erss.2015.06.007 Elsevier Ltd.

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

Brissaud, J. B. (2005). The meanings of entropy. *Entropy.*. https://doi.org/10.3390/e7010068.

Castán Broto, V., et al. (2018). Energy justice and sustainability transitions in Mozambique. *Applied Energy*, *228*(July), 645–655.

Castillo, H. P., Mendoza, D. A., & Caballero, M. P. (2012). Analysis of physicochemical properties of Mexican gasoline and diesel reformulated with ethanol. *Ingeniería Investigación y Tecnología*, *XIII*(número 3), 293–306.

CFE (2014). *Tarifas Domésticas CFE 2014 (Household Tariffs 2014).* Tarifas Domésticas.

Chakrabarti, B. K. (2013). In A. Chakraborti, S. R. Chakravarty, & A. Chatterjee (Eds.), *Econophysics of income and wealth distributions*. Cambridge: Cambridge University Press.

Chakravarty, S. R., & Ghosh, S. (2009). A model of income distribution. *New Economic Windows*, *8*(250), 192–203. https://doi.org/10.2307/2227127 MacMillan and Co. Limited.

Chatterton, T. J., et al. (2016). Mapping household direct energy consumption in the United Kingdom to provide a new perspective on energy justice. *Chemical Physics Letters*, *18*, 71–87. https://doi.org/10.1016/j.erss.2016.04.013 Elsevier Ltd.

CONAFOR (2013). *Bosques de Mexico frente al Cambio climatico*. Mexico City: Comision Nacional Forestal Available at:http://www.conafor.gob.mx/biblioteca/Manual-de-la-Lena.pdf.

CONAFOR (2014). *Anuario Estadístico de la Producción Forestal 2014.*

Das, R. R., Martiskainen, M., & Li, G. (2022). Quantifying the prevalence of energy poverty across Canada: Estimating domestic energy burden using an expenditures approach. *Canadian Geographer*, 1–18. https://doi.org/10.1111/cag.12750.

Day, R., Walker, G., & Simcock, N. (2016). Conceptualising energy use and energy poverty using a capabilities framework. *Energy Policy*. https://doi.org/10.1016/j.enpol.2016.03.019.

Dias, R. A., Mattos, C. R., & Balestieri, J. A. P. (2006). The limits of human development and the use of energy and natural resources. *Energy Policy*. https://doi.org/10.1016/j.enpol.2004.09.008.

European Commission (2021). *What is energy poverty?* Energy Poverty Advisory Hub Available at:https://energy-poverty.ec.europa.eu/energy-poverty-observatory/what-energy-poverty_en (Accessed 15 October 2021).

Franco, A., & Velázquez, M. (2016). Una aproximación sociodemográfica al consumo de energía en los hogares mexicanos, 2014. *La situación demográfica de México 2016* (pp. 159) (181).

García, R. (2014). *Pobreza energética en América Latina.* Comisión Económica para América Latina y el Caribe (CEPAL).

García-Ochoa, R., & Graizbord, B. (2016a). Privation of energy services in Mexican households: An alternative measure of energy poverty'. *Energy Research and Social Science*, *18*, 36–49. https://doi.org/10.1016/j.erss.2016.04.014 Elsevier Ltd.

García-Ochoa, R., & Graizbord, B. (2016b). Spatial characterization of fuel poverty in Mexico. An analysis at the subnational scale. *Economía, sociedad y territorio.*

Gillard, R., Snell, C., & Bevan, M. (2017). Advancing an energy justice perspective of fuel poverty: Household vulnerability and domestic retro fi t policy in the United Kingdom. *Energy Research & Social Science*, *29*(May), 53–61. https://doi.org/10.1016/j.erss.2017.05.012 Elsevier.

Goldemberg, J. (2001). Energy and human well-being. *Energy.*, *1*, 1–16.

Guruswamy, L. (2010). Energy justice and sustainable development. *Colorado Journal of International Environmental Law and Policy*, *21*(2), 1–416.

Heffron, R. J., & McCauley, D. (2017). The concept of energy justice across the disciplines. *Energy Policy*, *105*(November 2016), 658–667. https://doi.org/10.1016/j.enpol.2017.03.018.

Hills, J. (2011). Fuel poverty: The problem and its measurement. *Ann. Physics*, *1*, 1–192.

Hills, J. (2012). Getting the measure of fuel poverty: Final report of the fuel poverty review. *Case report 72* (doi: ISSN 1465-3001).

Howden-Chapman, P., et al. (2012). Tackling cold housing and fuel poverty in New Zealand: A review of policies, research, and health impacts. *Energy Policy*. https://doi.org/10.1016/j.enpol.2011.09.044.

IEA (2020). Defining energy access: 2020 methodology. Available at:https://www.iea.org/articles/defining-energy-access-2020-methodology (Accessed 19 February 2022).

INEGI (2015). *Ingresos Y Gastos De Los Hogares Enigh 2014.*

INEGI (2021). *INEGI - Vehículos de Motor Registrados en Circulación (motor vehicles registered in circulation)*.

International Energy Agency (2004). World energy outlook chapter 10: Energy and development. *World energy outlook*.

Jenkins, K. (2018). Setting energy justice apart from the crowd: Lessons from environmental and climate justice. *Energy Research and Social Science*, *39*(September 2017), 117–121. https://doi.org/10.1016/j.erss.2017.11.015 Elsevier.

Jenkins, K., Mccauley, D., et al. (2016a). Energy justice: A conceptual review. *Energy Research & Social Science*, *11*, 174–182 Elsevier Ltd.

Jenkins, K., McCauley, D., et al. (2016b). Energy justice: A conceptual review. *Energy Research and Social Science*, *11*, 174–182. https://doi.org/10.1016/j.erss.2015.10.004 Elsevier Ltd.

Jenkins, K. E. H., et al. (2021). The methodologies, geographies, and technologies of energy justice: A systematic and comprehensive review. *Environmental Research Letters*, *16*(4). https://doi.org/10.1088/1748-9326/abd78c.

Jiang, L., & O'Neill, B. C. (2004). The energy transition in rural China. *International Journal of Global Energy Issues*.. https://doi.org/10.1504/ijgei.2004.004691.

Kalecki, M. (1945). On the Gibrat distribution. *Econometrica*, *13*(2), 161. https://doi.org/10.2307/1907013 Evanston: Blackwell Publishing Ltd..

Lawrence, S., Liu, Q., & Yakovenko, V. M. (2013). Global inequality in energy consumption from 1980 to 2010. *Entropy*.. https://doi.org/10.3390/e15125565.

Lewis, P. (1982). Fuel poverty can be stopped. *National Right to Fuel Campaign*, *1*, 1–220.

Li, K., Lloyd, B., Liang, X. J., et al. (2014). Energy poor or fuel poor: What are the differences? *Energy Policy*, *68*, 476–481. https://doi.org/10.1016/j.enpol.2013.11.012 Elsevier Ltd.

Lowans, C., et al. (2021). What is the state of the art in energy and transport poverty metrics? A critical and comprehensive review. *Energy Economics*, *101*, 105360. https://doi.org/10.1016/j.eneco.2021.105360 Elsevier B.V..

Mantegna, R. N., Stanley, H. E., & Chriss, N. A. (2000). An introduction to econophysics: Correlations and complexity in finance. *Physics Today*. https://doi.org/10.1063/1.1341926.

Martínez, D. M., & Ebenhack, B. W. (2008). Understanding the role of energy consumption in human development through the use of saturation phenomena. *Energy Policy*. https://doi.org/10.1016/j.enpol.2007.12.016.

Martiskainen, M., et al. (2021). New dimensions of vulnerability to energy and transport povertyJoule. Elsevier Inc.*5*(1), 3–7. https://doi.org/10.1016/j.joule.2020.11.016.

Max-neef, M. A., Hopenhayn, M., & Hamrell, S. (1992). *Human scale development: Conception, application and further reflectionsVolume 1.*.

McCauley, D., et al. (2013). Advancing energy justice: The triumvirate of tenets. *International Energy Law Review*, *32*, 107–116.

Ministry of Fuel and Power (1946). *Domestic fuel policy: Report by the Fuel and Power Advisory Council*.

Montroll, E. W. (1981). On the entropy function in sociotechnical systems. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.78.12.7839.

Monyei, C. G., et al. (2018). Examining energy sufficiency and energy mobility in the global south through the energy justice framework. *Energy Policy*, *119*(April), 68–76. https://doi.org/10.1016/j.enpol.2018.04.026 Elsevier Ltd.

Monyei, Chukwuka G., et al. (2019). Response to Todd, De Groot, Mose, McCauley and Heffron's critique of "Examining energy sufficiency and energy mobility in the global south through the energy justice framework". *Energy Policy*, *133*(August), 1–5. https://doi.org/10.1016/j.enpol.2019.110917.

Morris, P. (1961). *Homes for today and tomorrow (the Parker Morris report)*.

Nye, D. E. (1999). Consuming power: a social history of american energies. *IEEE Transactions on Professional Communication*. https://doi.org/10.1109/tpc.1999.768169.

OECD (2016). Research ethics and new forms of data for social and economic research. *OECD science, technology and industry policy papers, no. 34. Vol. 34.*. OECD Publishing. https://doi.org/10.1787/5jln7vnpxs32-en.

Olawumi Israel-Akinbo, S., Snowball, J., & Fraser, G. (2018). An investigation of multidimensional energy poverty among South African low-income households. *South African Journal of Economics*, *86*(4), 468–487. https://doi.org/10.1111/saje.12207.

Owen, G. (2010). *Review of the UK fuel poverty measure: Report for Ofgem.* (London).

Pablo, Q. S., Paloma, T. de L. P., & Francisco, J. T. (2019). Energy poverty in Ecuador. *Sustainability (Switzerland)*, *11*(22), 1–19. https://doi.org/10.3390/su11226320.

Parajuli, R. (2011). Access to energy in Mid/Far west region-Nepal from the perspective of energy poverty. *Renewable Energy*, *36*(9), 2299–2304. https://doi.org/10.1016/j.renene.2011.01.014 Elsevier Ltd.

Pasternak, A. D. (2001). Global energy futures and human development: A framework for analysis. *Global 2001 international conference on: '"Back-end of the fuel cycle: from research to solutions"* (France).

Poruschi, L., & Ambrey, C. L. (2018). Densification, what does it mean for fuel poverty and energy justice? An empirical analysis. *Energy Policy*, *117*(January), 208–217. https://doi.org/10.1016/j.enpol.2018.03.003 Elsevier Ltd.

Price, L. L., & Rowntree, B. S. (1902). Poverty: A study of town life. *The Economic Journal*.. https://doi.org/10.2307/2957025.

Reynolds, T. S., & Hughes, T. P. (1984). Networks of power: Electrification in western society, 1880–1930. *Technology and Culture*.. https://doi.org/10.2307/3104214.

Robinson, C., & Mattioli, G. (2020). Double energy vulnerability: Spatial intersections of domestic and transport energy poverty in England. *Energy Research and Social Science*, *70*(July), 101699. https://doi.org/10.1016/j.erss.2020.101699 Elsevier.

Sánchez-Peña, L. (2012). Hogares y consumo energético en Mexico. *Revista Digital Universitaria*, *13*, 1–8.

Santos González, A., Estrada Lugo, E. I. J., & Rivas Lechuga, G. (2012). Uso de la leña y conservación del bosque en el volcán Huitepec, Chiapas, México. *LiminaR Estudios Sociales y Humanísticos*, *10*(1), 138–158. https://doi.org/10.29043/liminar.v10i1.41.

Sareen, S., et al. (2022). Double energy vulnerability in the Norwegian low-carbon urban transport transition. *People, Place and Policy Online*(September 2021), 1–20. https://doi.org/10.3351/ppp.2022.3953567323.

Schlosberg, D. (2003). The justice of environmental justice: Reconciling equity, recognition and participation in a political movement. *Moral and political reasoning in environmental practice*.

Semieniuk, G., & Weber, I. M. (2020). Inequality in energy consumption: statistical equilibrium or a question of accounting conventions?: Energy inequality: statistical equilibrium or accounting convention? *European Physical Journal: Special Topics*, *229*(9), 1705–1714. https://doi.org/10.1140/epjst/e2020-900125-5.

Sen, A. (1981). *Poverty and famines: An essay on entitlement and deprivation: The Great Bengal Famine.* Oxford University. https://doi.org/10.1093/0198284632.001.0001.

SENER (2014). *Sistema de Información Energética (Energy Information System)*. SIE.

Shannon, C. E. (1948). A mathematical theory of communication. *Bell System Technical Journal*.. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x.

Sheinbaum, C., Martínez, M., & Rodríguez, L. (1996). Trends and prospects in Mexican residential energy use. *Energy*.. https://doi.org/10.1016/0360-5442(96)00011-4.

Silva Aparicio, M., Castro Ramírez, A. E., & Perales Rivera, H. R. (2018). Áreas Voluntarias de Conservación y la extracción de leña en núcleos agrarios de Oaxaca. *Ecosistemas y Recursos Agropecuarios*, *5*(15), 435–449. https://doi.org/10.19136/era.a5n15.1743.

Snell, C., Bevan, M., & Thomson, H. (2015). Justice, fuel poverty and disabled people in England. *Energy Research and Social Science*, *10*, 123–132. https://doi.org/10.1016/j.erss.2015.07.012 Elsevier Ltd.

Sorrell, S., Gatersleben, B., & Druckman, A. (2020). The limits of energy sufficiency: A review of the evidence for rebound effects and negative spillovers from behavioural change. *Energy Research and Social Science*.. https://doi.org/10.1016/j.erss.2020.101439.

Sovacool, B. K. (2015). Fuel poverty, affordability, and energy justice in England: Policy insights from the Warm Front Program. *Energy*, *93*, 361–371. https://doi.org/10.1016/j.energy.2015.09.016 Elsevier Ltd.

Sovacool, B. K., & Dworkin, M. H. (2015). 'Energy justice: Conceptual insights and practical applications. *Applied Energy*, *142*, 435–444. https://doi.org/10.1016/j.apenergy.2015.01.002 Elsevier Ltd.

Sovacool, B. K., et al. (2012). What moves and works: Broadening the consideration of energy poverty. *Energy Policy*. https://doi.org/10.1016/j.enpol.2011.12.007.

Sovacool, B. K., et al. (2016). Energy decisions reframed as justice and ethical concerns. *Nature Energy*.. https://doi.org/10.1038/nenergy.2016.24.

Sovacool, B. K., et al. (2017). New frontiers and conceptual frameworks for energy justice. *Energy Policy*, *105*(January), 677–691. https://doi.org/10.1016/j.enpol.2017.03.005 Elsevier Ltd.

Thomas, S., et al. (2019). Energy sufficiency policy for residential electricity use and per-capita dwelling size. *Energy Efficiency*.. https://doi.org/10.1007/s12053-018-9727-4.

Thomson, H., et al. (2022). Understanding, recognizing, and sharing energy poverty knowledge and gaps in Latin America and the Caribbean – because conocer es resolver. *Energy Research and Social Science*, *87*(December 2021). https://doi.org/10.1016/j.erss.2021.102475.

Tundys, B., Bretyn, A., & Urbaniak, M. (2021). Energy poverty and sustainable economic development: An exploration of correlations and interdependencies in european countries. *Energies*, *14*(22). https://doi.org/10.3390/en14227640.

UN (2020). *The sustainable development goals report 2020New York*. *https://doi.org/10.4324/9781003099680-3*.

Van Veelen, B., et al. (2019). What can energy research bring to social science? Reflections on 5 years of Energy Research & Social Science and beyond. *Energy Research & Social Science*, *57*(July), 101240. https://doi.org/10.1016/j.erss.2019.101240 Elsevier.

Yao, X., et al. (2020). Inequalities by energy sources: An assessment of environmental quality. *PLoS One*, *15*(3), 1–28. https://doi.org/10.1371/journal.pone.0230503.