From Europe to Mexico: adapting prevailing metrics of energy affordability to assess Mexican energy poverty

Abstract

Access to energy services is determinant for household's development; hence, it is also a source of inequality. When a household is unable to attain adequate levels of energy services, due to infrastructural and/or affordability constraints, it is said to be experiencing energy poverty. In recent years, Mexico has been growing academic and policy interest in this topic, and a subsequent search for appropriate indicators.

This paper starts by reviewing the energy poverty literature on metrics, conceptualisations, and the use of indicators. It then focuses on transferring prevailing expenditure-based approaches from Europe to calculate the energy poverty ratio of Mexican households, applying the metrics 2M, M/2 exp., and LIHC. Most importantly, it proposes a new Low-income Low-Cost (LILC) metric, with the purpose of recognizing a household's mistaken energy poverty due to energy-efficient buildings. It further captures the most relevant drivers through a logit analysis and defines the required investment to tackle energy poverty. This paper seeks to retrieve existent underutilized literature and measurement approaches from Latin American countries and transfer new insights applying European metrics to non-European contexts.

Keywords

Energy Poverty, Expenditure, Energy Services, Affordability, Indicators, Low-income Low-cost

1. Introduction

To achieve Sustainable Development Goal 7 it is necessary to recognise the connections throughout different problems within energy and economic systems. For the Mexican case, we find household inability to afford energy sits at the nexus of a 46.2% poverty rate [1], the highest levels of income inequality, and the highest energy prices amongst the Organisation for the Economic Co-operation and Development (OECD) countries [2].

In 2013, a reform to the Mexican energy system was proposed as a response to the various events that led to an energy crisis, the depletion of the most abundant oil reserves, infrastructure obsolescence causing energy unavailability, plus the global compromise for climate action. Social elements related to the domestic demand sector were incorporated as one of the main objectives of the National Energy Strategy 2014-2028 in Mexico [3]. Yet, there are no specifications of any aspects to consider or procedures to measure and monitor the domestic energy sector. Notwithstanding, Mexico's progress in social energy and demand-side studies is slow, being energy access, the strongest interest translated into the simple bilateralism of having energy access or not. With an electrification rate of 99.2%, research and policy concerns should focus on aspects beyond the infrastructural access to energy [4], drawing on more experienced regions like Europe to add more complexity to our understanding in the country.

In the last decades, concepts such as energy poverty have been developed motivated by the impact of energy on society's wellbeing as well as the relevance of studying the characteristics of the energy demand side. Energy poverty is a concept that emerged in Europe during the late 1970s as a response to an oil crisis and household inability to achieve adequate internal temperatures during cold weather seasons. Besides winter death, energy poverty intensifies poverty and widens the inequality gap [5,6], by precluding household's productivity, educational performance and gender inequality [7,8] creating an information barrier and exposing them to "eat or heat" disjunctive choices [9,10].

The need to address energy poverty has spread through Latin American countries where the energy and economic context differ from that in Europe, demanding studies and methods suitable to the developing America. For the same reason, many approaches have flourished in trying to explain and understand energy poverty as the impossibility to satisfy household's energy needs through access to energy services such as communication, food preservation and transport [11,12]. In addition to the application of the *Fuel Poverty Potential Risk Index* for social housing allocation applied in Chile [13].

Several metrics can be used to calculate the household's energy poverty rate in a region [14–18]. Yet, measuring energy poverty is the initial step towards solving the problem. More important is to carry out an analysis to uncover the factors driving its prevalence, that way, not just the number of households in energy poverty can be known, but also the reasons why [19–22]. Once aware of the energy poverty drivers, it is possible to generate targeted policies to inhibit them and subsequently alleviate it. Empirical studies from the developing world typically apply the expenditure-based approach and perform an econometric analysis to identify the main drivers [19,20]. To assist the task, various statistical indicators can be analysed to contribute to a better understanding and detection of conspicuous relations, providing useful guidance for designing effective policies[23].

Given the literature and the socio-political context, the aim of this research is to measure energy poverty from the Mexican household's internal domestic energy system through an expenditure-based approach.[3] Appraising the affordability issue, by testing the 'High share of energy costs', 'Low available income', and 'Insufficient energy spending' through the 2M, M/2 exp. and LIHC metrics. Based on the absence of a metric that distinguished lower-income households this article proposes the incorporation of the metric LILC 'low-income low-share' complementing 'insufficient energy spending' with 'low available income'. To understand and determine the main economic, demographic, and infrastructural drivers leading to affordability-energy poverty in the Mexican case study, we performed a logistic regression that analysed the influence of 25 variables on being energy poor or not.

2. Literature and methodological review

2.1 Energy poverty conceptualization and studies

The energy poverty literature exhibits a large variety of studies and definitions, where authors try to explain the phenomenon through the application of different tools and addressing it according to the specific theoretical points of reference, applicable to each case study.

2.1.1 Energy outcomes-based approach

This approach is based on the impacts energy poverty has on household members. For example, lacking modern energy services[5], by not being connected to the grid, could reduce productivity [20,24–26], impact upon children's education [8,26,27], and the health of those exposed to coal burning during food preparation or those whose dwelling is inadequately heated [24,25,28,29]. This is additional to the environmental impacts of deforestation and generation of atmospheric emissions [24,25,30].

Although the literature is scarce, some efforts can be distinguished, one example are Mirza & Sirzmai [31] who carried out an opportunity cost study for the time spent in energy source collection in rural Pakistan, by developing a survey to assess the factors impacting the welfare of the population through the satisfaction of their household energy needs [31]. The authors developed a composite index that considers energy inconveniences and shortfalls. These include time spent on collection, the frequency of buying, household health; distance from household travelled and household's member's involvement. The research found that 23.1% of households in rural Pakistan experienced energy inconveniences and 96.6% experienced energy shortfalls [31]. This approach, as well as the index developed by the authors, are hard to replicate at the national level because of the costs and time required to do so, although it is suitable for local circumstances and adaptable to different contexts.

In addition to the opportunity cost outcome, Culver makes reference to environmental impacts, health impacts, and absence of choice as outcomes that could be measured [17].[6] Health impacts can usually be calculated by comparing mortality rates during the winter with other times of the year and relating them to building efficiency causes. Healy's findings regarding winter deaths in European countries revealed a correlation between winter deaths,

[3] Internal domestic energy excludes energy needs, consumption and expenditure for transport or any other activities outside the dwelling scope.

[5] Modern energy services are defined by the IEA (2014) as a 'household access to electricity and clean cooking facilities'.

[6] Amartya's Sen absence of choice refers to the lack of services satisfiers and the scarce opportunities that poverty offers them [70].

and poor building efficiency conditions [28]. Some of these outcomes bear data availability difficulties, which could be a limitation for implementation. Moreover, the complicated task of assigning causality to a problem where various factors are involved, along with the complexity of measuring social and health-related outcomes, are further barriers to utilizing this approach [32]. Unlike other approaches, the outcome-based does not explore the phenomenon beyond energy poverty's 'headcount ratio' neglecting its root causes.

2.1.2 Energy needs/services-based approach

Energy poverty is defined as "the privation of energy services linked to satisfy basic needs"[11], to alleviate energy poverty in developing countries "modern energy services…in a way that is economically viable, sustainable, affordable and efficient, and that releases the least amount of GHGs" must be provided [33]. The energy services approach breaks down the energy-wellbeing relationship, because households "do not demand energy per se, but energy services" [34] such as heating and cooling, cooking, information, lighting, and food refrigeration [35].

Some of the metrics developed under this approach include energy sufficiency, deprivation, energy service quality, energy access, needs and energy delivered, applied mostly to understand energy poverty in developing countries. The multi-dimensional Energy Poverty Index was developed in 2011, with the intention of being a cross-country application. Based on household energy service indicators from all African countries where the necessary data was available, households were classified according to their energy poverty degree, ranging from acute to moderate. Considering a household to be energy poor if it was lacking any of the several dimensions used in the study[23].

Later on, in 2016, inspired by the energy services deprivation approach, Ochoa & Graizbord [11] carried out the same metric in a Mexican case study. Using secondary data from the National Survey on Households Income and Expenditure (ENIGH), the authors distinguished the dimensions water heating, food cooking, food refrigeration, lighting, ventilation or air conditioning, and entertainment. Part of their methodology was a cluster analysis and logistic regression; the outcomes of the multivariate analysis were 7.2% of Mexican households were deprived of 4 out of 6 energy dimensions, therefore called "strong energy poor". Another 5.6% of the households were deprived of 5 out of 6 dimensions, equivalent to being "extreme energy poor", 3.8% were deprived of the food-cooking dimension and 12.7% of food-refrigeration. Equivalent to 8,900,000 Mexican households in energy poverty by the energy services deprivation approach [11].

Despite being an approach that can be easily implemented if data is available, and that can be replicated internationally recognising variations between national and regional levels [8], this approach suffers from inconsistencies. One of the limitations is that conceptions and election of dimensions vary among researchers and surveys [35], and does not capture the intensity or the socioeconomic circumstances of those under energy poverty, precluding any targeted policies.

2.1.3 Energy access- based approach

Energy access possesses many definitions at the international and national level accounting for different indicators. The International Energy Agency (IEA) considers that energy access "is about providing modern energy services to everyone around the world. These services are defined as household access to electricity and clean cooking facilities" [36]. In addition to this definition, the World Energy Outlook includes elements related to economic productivity, public health and education as well as a threshold of a minimum level of electricity supply [37]. Access to modern energy has been used as a proxy for energy poverty internationally; considered, overall, a convenient energy poverty indicator for its reduced cost, simple calculation, and communication [17].

At a first glance, energy access as an energy deprivation indicator could seem a positive achievement in energy and developmental concerns, but the ratio excludes measures of "quality, availability, reliability, adequacy, affordability, convenience and safety" [38]. This means a household could have access to electricity and at the same time be unable to use the service, due to reasons of affordability. Simultaneously people may have access to free or cheaply available biomass energy sources and make use of this instead. Elsewhere, this indicator has been criticised for leading to the implementation of superficial policy measures, with the sole aim of reducing the population ratio with electricity access deficit.

2.1.4 Consensual-based approach

This alternative approach to energy poverty was applied by Healy (2004) across the European Union and is grounded on consensual poverty measures. Typically, this involves households answering questions regarding domestic energy affordability such as bill payment punctuality and keeping their home warm. Similarly, questions about leaks, damp walls, and other building efficiency characteristics are asked [40,41].

Healy estimates that with the application of surveys, it can be assessed if people live in energy poverty conditions, just by asking them. According to various academics [42,43], one of the contributions of this approach is the capacity to capture energy poverty prevalence, portraying a broader energy poverty experience by asking for people's energy poverty perceptions and experiences [42]. The approach is preferred for its inclusive character by Day, Walker and Simcock [8], but others like Ochoa & Graizbord [11] consider this approach to be identifying "people's perceptions of energy-related standards" rather than measuring energy poverty. It has also been criticised for its subjective nature [32], whereas others believe it is "an effective combination between subjective and objective" [41]. Like any other energy poverty metric, it lacks in certain areas. The most documented limitation reported in the literature is the difficulty to interpret the results due to its reliance on judgements and views of the population [11,32,44]. More importantly, the approach could lead to self-exclusion/inclusion[10] from/into energy poverty according to people's perceptions of self [40,45].

2.1.5 Expenditure-based approach

Energy poverty is defined by the ability to access and consume energy services considering affordability. Many researchers and states widely use the following energy poverty approach, because of the challenging task of measuring energy poverty under the logic of other approaches. Labelled as the 'energy inputs' approach by Culver [17], as the name of the approach suggests, it is indeed derived from the household's energy expenditure indicators. Assessing energy poverty through energy consumption, or income assigned to domestic energy expenditure, it typically measures energy expenditure/consumption in monetary and non-monetary units (e.g. KWh) [17,32]. The assumption of this approach regarding energy services is that if households afford energy, they can access those energy services.

[10] In comparison with an expenditure-based approach, the data overlapped and people who in terms of expenditure was considered energy poor did not consider themselves to be so [40], and the opposite.

Affordability represented by expenditure and income is measured in many ways that can be roughly classified as follows:

- High share of energy cost:

Are metrics that compare the household's energy expenditure to a certain threshold, those whose energy spending lies above it are considered energy poor.

- Low available income:

This metric sets a certain threshold to compare it with the household's income after energy costs, a disposable income enough to satisfy the household's basic needs.

- Insufficient energy spending:

Perhaps, the opposite premise of 'high share of energy spending', household expenditure is compared to a certain threshold, considering energy-poor households as those whose energy spending is below the threshold. Under this premise, Miniaci, Scarpa and Valbonesi [46] used the term 'residual income poor' where households are energy poor if the actual energy expenditure is below a threshold (minimum standard energy expenditure), classifying those households as 'under-consumers'. Each of the metrics above has trade-offs; energy expenditure insufficiency could be explained by highly efficient energy households, similarly, high expenditure is likely to overestimate the performance of high-income households considering them energy poor, even if they exceed by far the standard energy expenditure required to have access to basic energy needs. Finally, the 'low available income' metric catalogues a household as energy poor by the size of the income left after energy expenditure, but ignores 'underspending', the fact that some households do not have the possibility to devote a higher share of energy expenses and the actual bundle does not cover the whole household energy needs [47].

2.2 Instruments behind the energy poverty metrics

Numerous adapted variations for different countries have been developed in the last decade. A fixed threshold like the 10% share of income was used for years to measure fuel poverty in some European countries but is disapproved by many academics' due to its lack of dynamism through time. Furthermore, a fixed threshold loses applicability in the constantly changing economy and lacks cross-national comparability. Yet, beyond its simplicity, there is a cheap and easy to communicate instrument [32,41].

Rademaekers et al., [32] reviewed many energy poverty metrics and instruments adequacy to measure and monitor energy poverty, suggesting *twice the median* (2M), *low-income/high-cost* (LIHC) and *half-median expenditure* (M/2 Exp) to be the most complete instruments to measure energy poverty. The overall advantage of these relies on the ease of actualization in time and the applicability at different levels and regions, providing a disaggregated energy poverty panorama at a low cost. 2M energy poverty captures household's energy expenditure larger than twice the national median expenditure. LIHC energy poverty measures the household's income after energy costs capturing those that fall below the poverty line and simultaneously the share of its income spent on energy is above the national median [32]. M/2 exp. captures households in energy poverty when their energy expenditure is lower than the national median divided by two. The expenditure-based approach has been adopted by many countries using the mentioned metrics and other variations, with the intention to make it suitable for the local energy context. In the attempt to overcome the limitations from the energy-expenditure approach, some countries and authors have combined the metrics, looking for complementarity within them. Belgium's approach to energy poverty combines the high-energy expenditure using the 2M (twice the median) instrument along with insufficient spending M/2 exp.

2.2.1 Supportive indicators to comprehend energy poverty

Alongside the energy poverty metrics and indicators, many supporting indicators have been used, whose objective is to provide a further understanding of the household, recognising any correlations or influence among any household factor and experiencing energy poverty. To provide a richer outlook of energy poverty as well to support a deeper understanding of the factors contributing to its presence, it is fundamental to incorporate indicators that by themselves are not sufficient to measure energy poverty, these are the so-called supporting indicators [32]. The supporting indicators provide a representation of the drivers of energy poverty correlated with the energy poverty metrics; moreover, they provide a basis to generate targeted policy. Expenditure-based indicators must capture the household's energy affordability if the consumption of energy services is adequate. The most recognized indicators are income, expenditure and price [15,32,48].

The application of critically evaluative affordability indicators, such as *energy spending* and *price* are for important policy-making purposes [49]. In relation to this, Sovacool acknowledge the relevance of them from an energy policy view, remarking how increasing energy prices restricting the households energy affordability was "functionally the same as if they lack access to energy services altogether"[50]. Indicators also provide valuable information about willingness to pay and the effects of increasing energy expenditure, as well as people's motivations to consume. Finally, there is still a consensus regarding budget constraints and the household energy system dependence [41].

2.3. Energy poverty gap

Another step beyond measuring the energy poverty headcount ratio, which provides the status quo of the problem, would be to figure out the energy poverty depth. Building on Foster's [51] indexes to measure fuel poverty, assessing the depth of energy poverty can be done by estimating the energy poverty gap index. This index does an approximate calculation of the average difference between the energy poor and the energy poverty line, subject to the metric applied [51], with the aim of evaluating the cost of alleviating energy poverty; either by measuring the income that households require, the amount of energy spending, or the appropriate energy price adjustments. In other words, it is a quantification of the energy poverty abatement which provides significant inputs for public policy design, either in the shape of financial support or energy price management [32,52,53].

2.4. Drivers of domestic energy deprivation: a multivariate analysis

Many energy poverty empirical studies have formulated the influence of drivers by operating econometric analysis, assigning energy poverty the role of the explanatory variable, and drivers and indicators as exploratory. John Healy and Clinch [55] as part of their several fuel poverty studies for Ireland and Europe they employed a multivariate *probit* regression analysis to understand the effects of fuel poverty on household occupancy in Ireland, in which the most featured finding was the elderly households propensity to suffer inadequate indoor temperatures during the winter. For the same case study, they explored the relationship between fuel poverty and socioeconomic/demographic variables. Finally, in 2002, applying the same multivariate analysis, the authors regressed various indicators at the European level, the outcome was the highest incidence of fuel poverty amongst lone-parent and lone-pensioners.

On the other side, developing countries empirical studies adopting the expenditure-based approach to determine energy poverty by headcount, additionally engage an econometric analysis with the logistic regression framework. A multiple logistic regression is suitable for a bivariate energy poverty result, where households are classified as 'energy poor' and 'not-energy poor'. This was the case with a study of Addis Ababa city in Ethiopia [56], in which the authors regressed the binomial energy poverty against several socio-physical drivers. The outcomes of the study revealed that family size, the educational level of the household head, energy expenditure, and total income were the most influential variables explaining multidimensional energy poverty. Similarly, Zaakirah and Khembo [19] and Ogwumike and Ozughalu [20] calculated Nigeria's and South Africa's expenditure-based energy poverty and its determinants, by the formulation of a logistic regression analysis. Amongst Nigeria's energy poverty findings, the most influential drivers were the household size, educational level, householder gender and age, region, and the general poverty situation. Likewise, the energy poverty drivers in South Africa are expenditure, race, location, energy access, educational level, household and dwelling size [19].

3. Methodology

3.1. Population sample and participants

The empirical analysis is based on the Mexican household's internal domestic energy. The household sample was drawn from ENIGH data for 2014, containing a sample of 19,479 households representing 31.6 million households in Mexico, from which 6.8% are in rural areas and 92.2% in urban areas. The sample population is geographically located in 49 different municipalities distributed along the 32 States of the Mexican Republic.

3.2. Expenditure-based indicators to measure energy poverty

In this study, residual income will be used as a proxy for income and the energy expenditure will be applied as the actual energy expenditure. Both income and expenditure were equivalised by the CONEVAL adult equivalent scale since they have to increase according to the size of the household [54,64].[11]The energy expenditure indicator is indispensable to measure energy poverty through the chosen metrics, being the independent variable. Unlike the rest of the metrics, LIHC and LILC involve income and the economic wellness lines that are helpful to calculate poverty in the Mexican population. Table 1 describes the set of indicators per energy poverty metric.

Table 1. Energy poverty measure: metrics and variables

DEPENDENT	INDEPENDENT	DESCRIPTION
LIHC	EEs_h	Adult equivalent income share of actual energy expenses
	$ResInc_h$	Adult equivalent residual income (after housing)
	$W_h{}^x \quad \forall x = r, u$	Poverty line, food and non-food basket, rural and urban*
2M	EEs_h	Adult equivalent income share of actual energy expenses
	$\mu(EEs_h)$	Energy expenditure share median***
M/2 EXP	EE_h	Adult equivalent monetary energy spending
	$\mu(EE_h)$	Energy expenditure median**

[11] Adult equivalent scale from 0-5 years =.79, 6-12=.74, 13-18=.71, 19 and above=.99 [71].

LILC	$ResInc_h$	Adult equivalent residual income (after housing)
	$W_{h^x} \quad \forall x = r, u$	Poverty line, food and non-food basket, rural and urban*
	EEs_h	Adult equivalent income share of actual energy expenses

*Poverty line rural=$1614.65 urban=$2542.13 per month in Mexican pesos [59]. **Energy Expenditure Median is $307.22 per household quarterly. ***Energy Expenditure Share Median is 2.97% per household quarterly. Own elaboration.

To prevent higher income populations being mistaken as energy poor through the "below the threshold" metrics such as the M/2 exp., the LILC (low-income, low cost) metric was incorporated. This uses the LIHC as reference except that the LILC takes into consideration those households whose energy expenditure share of income is below the median.

3.3 Selecting supporting indicators to assess the drivers of energy poverty

For the purposes of this research, the supporting indicators were chosen based on data availability and limited by the lack of an energy survey and/or domestic sector energy monitoring in Mexico. Measuring the influence of each indicator driving energy poverty was made through a logistic regression. The equation variables are as follows:

Table 2. Energy Poverty Drivers

CATEGORY	VARIABLE	DEFINITION
TREATMENT		
INCOME / EXPENDITURE	Tot_Exp	Household's total monthly expenditure
	EQ_TotExp	Equivalised household's total energy expenditure per month
	EE	Households total energy expenditure per month
	EEs	Households total energy expenditure share per month
	Tot_ResInc	Total monthly income per household before housing expenses
	EQ_ResInc	Equivalised total monthly income before housing expenses
ENERGY PRICE*	P_Elect	Domestic electricity price per month by State
	P_LPG	LPG price per kilo by each State of the Republic
AUXILIAR	Geo_Loc	Geographic location per locality, municipality, and state
	HH_Folio	The numerical figure used to distinguish each household
	EQ_EE	Equivalised total monthly expenditure per household
	W	Wellness line set by CONEVAL**
CONTROL		
DEMOGRAPHIC	Strata	Socioeconomic Strata from CONAPO: Low, Medium Low, Medium High, High
	Hhder_Gender	Householder gender: Female, Male
	HH_Size	Number of household members
	Region	Household on urban or rural location
	Underage	Number of household members below age 12
	Adults	Number of Household members 12< & <65
	Over65	Number of members over the age 65
	Tenancy	Dwelling tenancy status: Rent, Lend, paying to own, own, under litigation, others
ENERGY DEMAND / SUPPLY	Fuel Cook	Most common fuel for cooking or heating food: firewood, coal, LPG, natural gas, electricity, other fuels
	Electricity Access	Source of access to electricity: public grid, private plant, solar panel, another source, no electricity
TECHNOLOGY /	Air Conditioner	If the dwelling possesses any air conditioner device
	Heating	If the dwelling possesses any heating system

EQUIPMENT	Biodigestor	If there is a biodigester system connected to the sewage service
EFFICIENCY	Age_Dwelling	Age of the building
	Incandescent_Bulb	Number of incandescent bulbs in the dwelling
	Saver_Bulb	Number of “energy efficient” light bulbs in the dwelling
	Water_heater	Water heater powered by gas or solar energy
	Age_Refrigerator	Age of refrigerator

*The energy variable is composed by the electricity price P_Elect. built with data from the National Index of Consumer Prices (INPC) for the year 2014 [60], the liquid petroleum gas variable P_LPG was built with data from [61].** the wellness line (W) data was gathered from CONEVAL (National Council for the evaluation of social development policy) [59], the rest of the variables were collected from the (ENIGH) national survey of households income and expenditure 2014 [62].

4. Data Analysis Procedure

4.1. Energy poverty headcount ratio

To calculate the 2M energy poverty the formula is given by:

$$EP_{2M} = \{EEs_h > 2(MEEs_n)\} \tag{1}$$

Where EEs_h is the energy expenditure share per household h; μEEs_n is the median μ from the sample n energy expenditure share EEs.

LIHC the formula is given by:

$$EP_{LIHC} = \begin{cases} \mu(EEs_n) < EEs_h \\ (Tot\_ResInc_h - EE_h) \leq W_{h^x} \end{cases} \quad \& \tag{2}$$

Where μ is the median of the ‘adult equivalent-residual income share’ assigned to energy expenditure from the total sample EEs_n ; $(Tot\_ResInc_h - EE_h)$ is the total income per household minus the energy expenditure and W_{h^x} is the wellness line per household region either urban or rural.

M/2 exp. the formula is given by:

$$EP_{HEP} = \left\{EE_h < (\frac{MEE_n}{2})\right\} \tag{3}$$

Where EE_h, is the energy expenditure per household, and $(\frac{MEE_n}{2})$ is half the national energy expenditure median.

LILC the formula is:

$$EP_{LILC} = \begin{cases} \mu(EEs_h) > EEs_h \\ \& \\ (Tot\_ResInc_h - EE_h) \leq W_{h^x} \end{cases} \quad (4)$$

To be considered energy poor, the energy expenditure share EEs_h must be below the median, and the income before energy costs must lead the households to poverty (below the wellness line W_{h^x}).

4.2. Logistic regression to measure the influence of energy poverty drivers

The empirical model is formulated as follows:

$$EP_m(0,1) = (Tot\_Exp_h - EE_h) + P_{Elect_h} + P_{lpg_h} + \cdots + \in \quad (5)$$

Where $EP_m(0,1)$ is the dependent dichotomous energy poverty variable for each of the indicators LIHC,2M, M/2 EXP & LILC., being EP_m (0) if households are not energy poor and (1) if households are energy poor. The explanatory variables are $(Tot\_Exp_h - EE_h)$ total expenditure after housing costs minus energy expenditure per household, understood as residual income and incorporated as a proxy for household's income. The variable capturing energy prices is separated into the two main domestic energy sources in the country, first, electricity prices (P_{Elect_h}), plus (P_{lpg_h}) LPG prices.

The logistic regression looks for the probabilities of being in the energy poverty or in the non-energy poverty groups, maximising the likelihood of an event to occur given the odds of belonging to any group [63–66]. To avoid violating normality and homoscedasticity assumptions, the maximum likelihood criterion was adopted in order to estimate the model. Finally, it is necessary to validate the regression trustworthiness by verifying the goodness of fit through the Chi^2 predictive accuracy and pseudo R^2 measures to represent the overall model fit; besides, testing for multicollinearity through the VIF test [65,66].

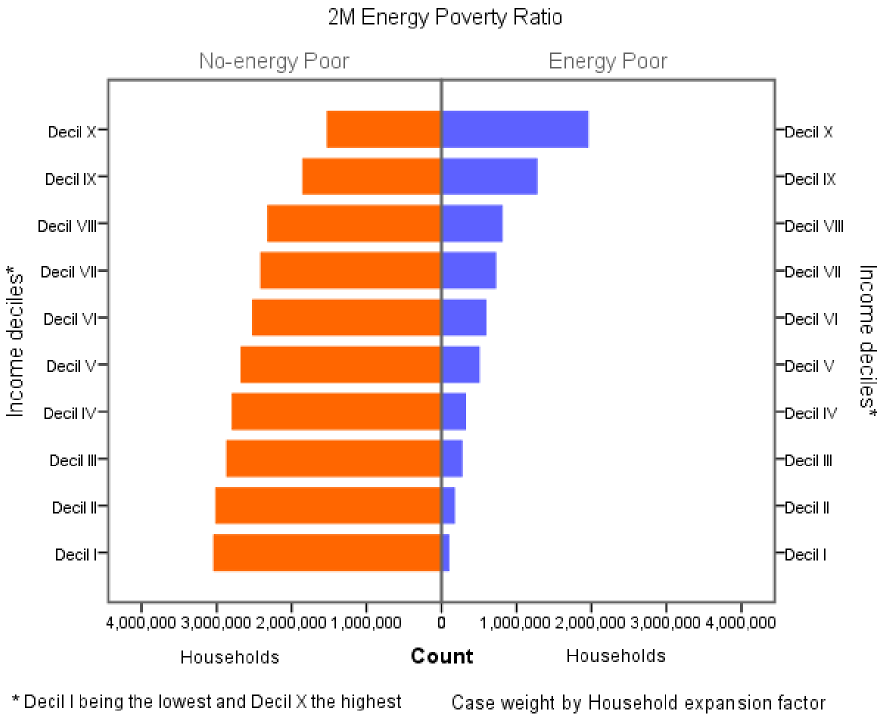
5. Results and Discussion

5.1. Energy poverty ratio findings

The 2M headcount ratio of energy-poor households is 6,914,349 equivalent to 23.2% of Mexican households. On the contrary, not-energy poor households account for 76.7% of the national sample corresponding to 24,756,653 households, which in total adds up to 31,671,002 households.

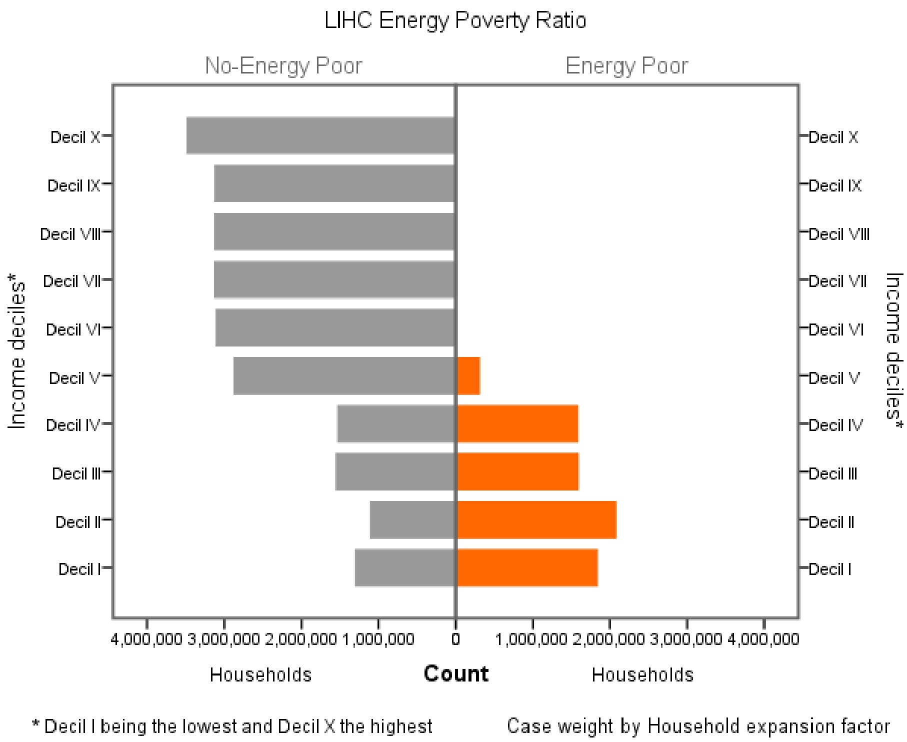
Notwithstanding is important to bear in mind the flaws of the 2M metric. As seen in Figure 1, some of the households considered energy poor could have been included on the category by their high share of income spent on energy due to the possibility of doing so; the high demand and consumption characteristic of higher-income households, which does not imply energy poverty.

Figure 1. Energy Poverty 2M



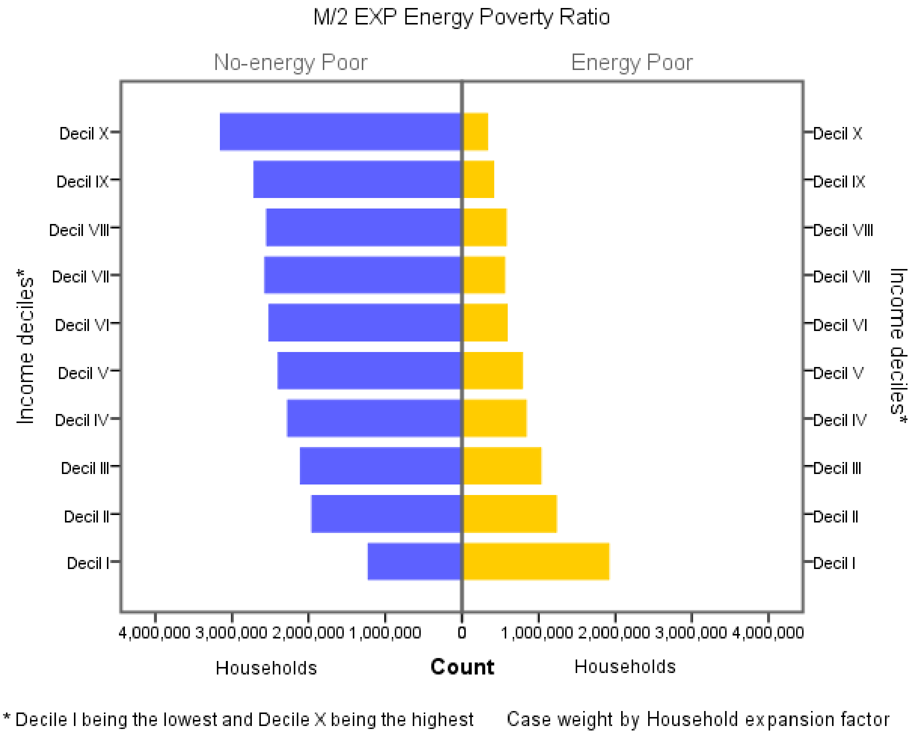
Energy poverty by the Low-income/High Share metric results were 76.8% of the Mexican population are not-energy poor (0) equivalent to 24,496,065 households, the rest 23.2% are experiencing energy poverty (1) corresponding to 7,372,859 households. One of the LIHC metric's strengths is the ability to distinguish energy poverty from income poverty (Figure 2), excluding high-income households avoiding the possibility of inflating the energy poverty headcount ratio by mistake.

Figure 2. Energy Poverty LIHC



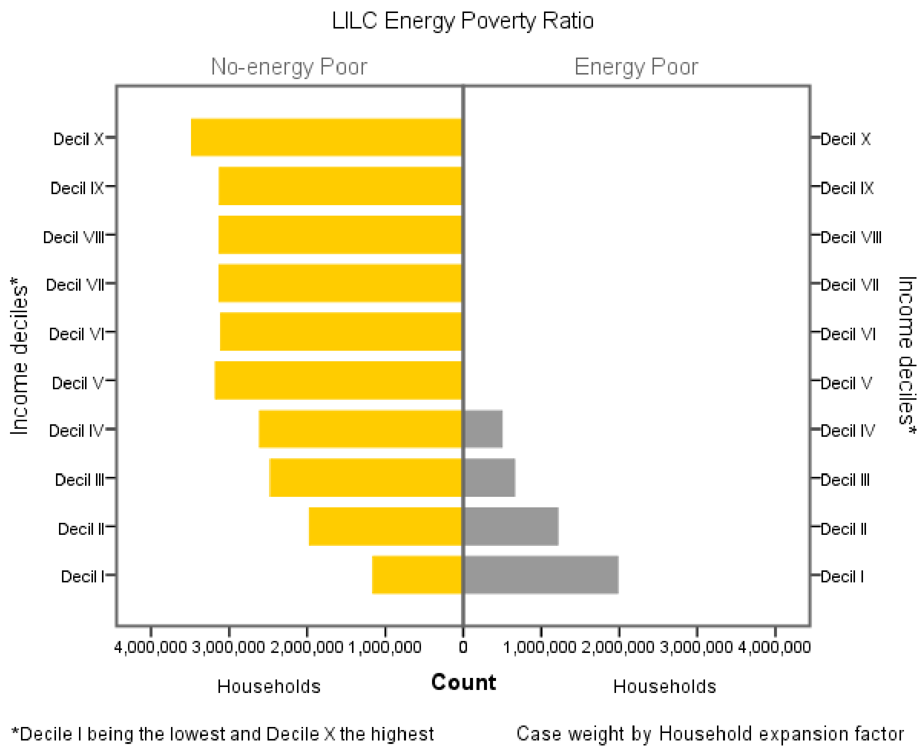
When it comes to the M/2 exp. the population in hidden energy poverty accounted for 26.1% of the sample, the same as 8,250,619 households. In addition, 23,420,383 households are not-energy poor accounting for 73.9% of the households.

Figure 3. Energy Poverty M/2 exp



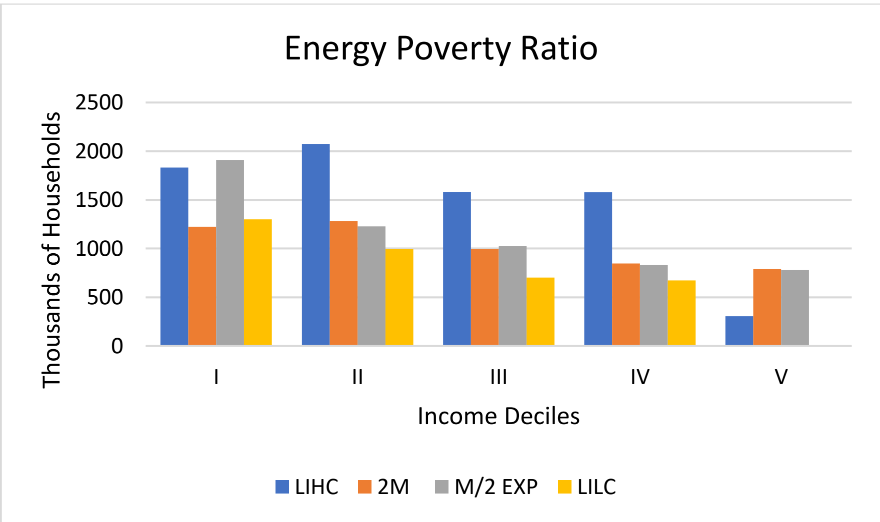
However, this metric can confuse highly efficient households as energy poor due to their lower than normal expenditure, also it could be related to the amount of time that household members spend at home depending on the household composition and income classification. Higher income households members are more likely to be employed than lower income members, besides, they have the capacity to engage in leisure activities away from home reducing the time for internal energy use as we can see in Figure 3. This is an error that can be mended by the Low-Income Low-Cost metric that manifested an energy poverty membership of 11.5% equivalent to 3.67 million households against an 88.4% of non-energy poor households equivalent to 28 million households. Figure 4 exhibits the membership to energy poverty from the four lower deciles of the economy.

Figure 4. Energy Poverty LILC



According to each of the energy poverty calculations, households that belong to the five lowest deciles of the economy are those who have greater chances to be energy poor. On the other hand, in some metrics such as 2M and M/2 exp. in which there are no distinctions between incomes, there is the possibility to consider a household energy poor for the wrong reasons, due to the higher energy consumption and efficiency that typically accompanies higher income households. The next figure summarises the energy poverty results per economic decile and number of households in México.

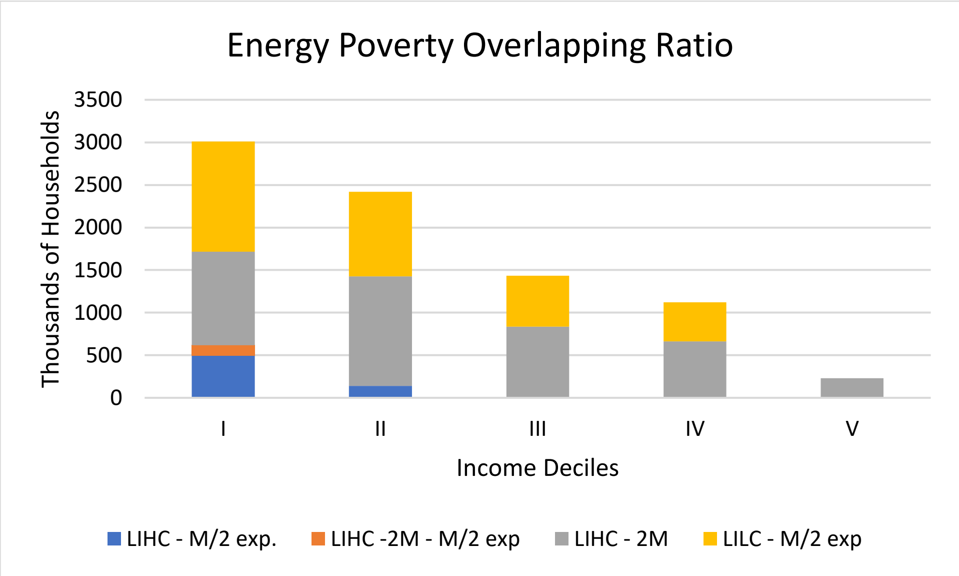
Figure 5. Energy Poverty Outline in México: 2M, LIHC, LILC & M/2 exp



Own elaboration based on the energy poverty calculation from this study. The information represents de economic deciles and millions of households in Mexico 2014.

As illustrated in figure 5, the energy poverty outcomes from each metric differ from one another, but also comes to our mind the possibility of being energy poor by more than one metric. Looking for membership along the 4 metrics the results revealed that 91% of the households on LILC energy poverty were as well energy poor through the M/2 exp. metric, equal to 3.3 million households.

Figure 6. Energy Poverty Overlapping Ratio



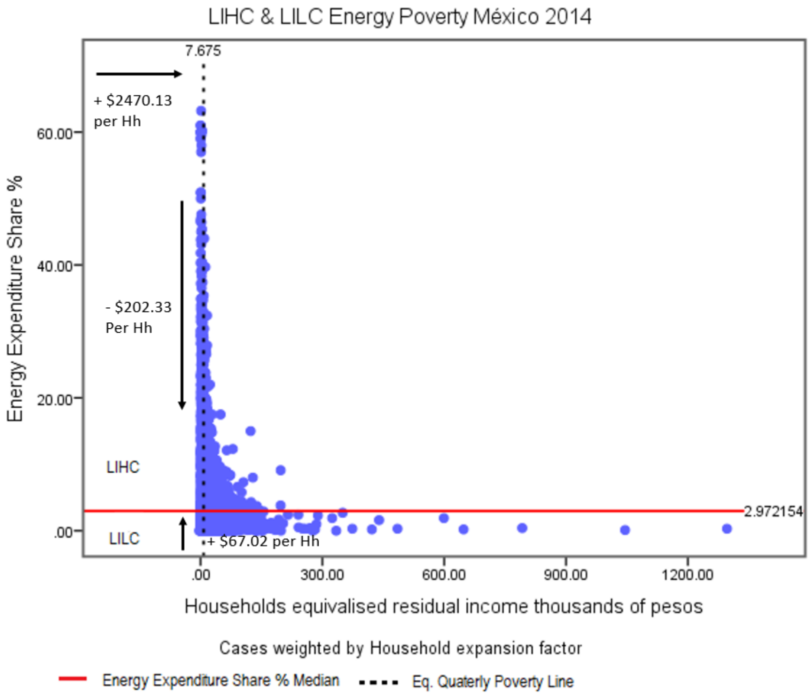
Own elaboration based on the energy poverty calculation from this study. The information represents de economic deciles and millions of households in Mexico from 2014

Comparing the results of each metric we found 8.2 million households in energy poverty, around 5 million households were energy poor by LIHC and other metrics (figure 6). This information can be relevant to target policies to those households more liable of being energy poor as well as complementing results in order to achieve a more accurate outcome.

5.3 Energy poverty gap

The gap that separates energy-poor households from the non-energy poor burden is given by the required amount to reach it. Via the LIHC metric results (figure 6), there is an average gap of $2470.13 per household, representing a total of 16.5 thousand million Mexican Pesos; the $2470.13 average gap represents how much the household's income needs to increase so as to be out of poverty after energy costs. In addition to this, the LIHC has a second gap which is the average energy expenses share from the total residual income, where there is necessary an average reduction of $202.33 pesos per household spent in energy to prevent being energy poor, which represents an overall amount of 1.1 thousand million pesos translated in energy share reduction.

Figure 7. Energy Poverty Gap LIHC & LILC

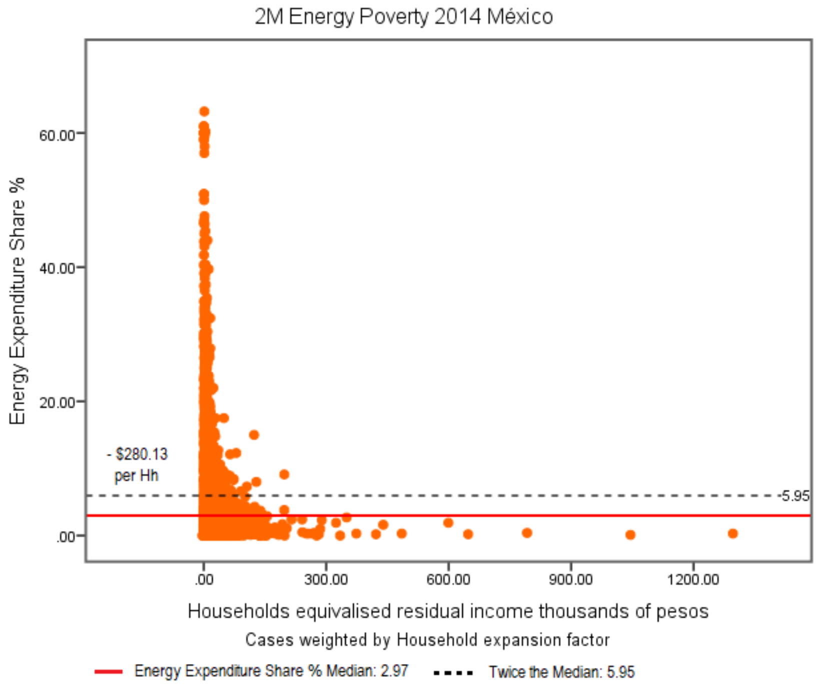


Own elaboration based on the energy poverty gap results from this study.

Similar to the LIHC, the LILC poverty gap requires an average quantity of $2038.97 pesos per household as an income increment, the total sums up to approximately 7.7 thousand million pesos to prevent households from falling into poverty after paying their energy bills. Regarding the energy expenses as income share, these should be increased by an average of $67.02 pesos, which represents a total of 239.2 million pesos necessary to be out of energy poverty if the income remains constant.

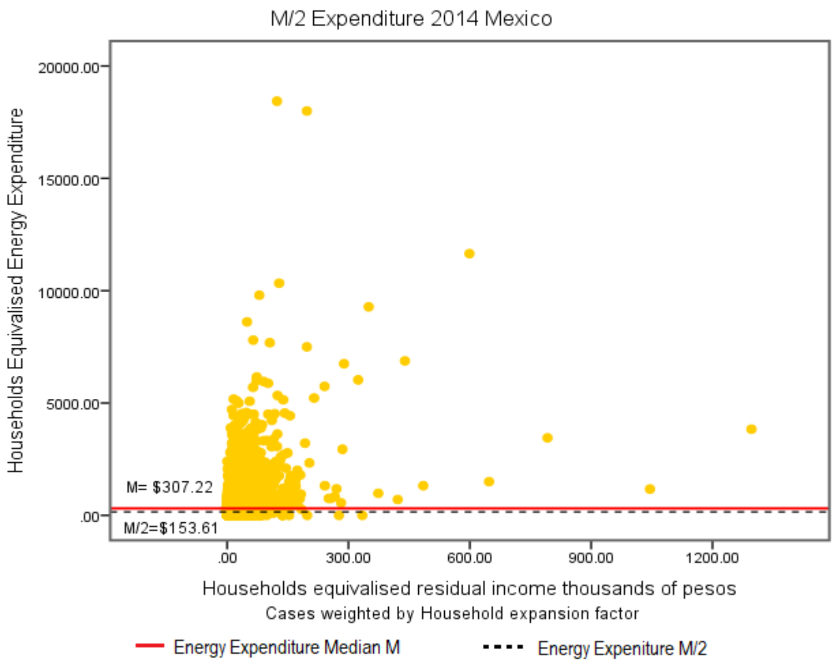
In contrast with the two metrics above, the 2M and M/2 exp. have only one way to measure the energy poverty gap. 2M energy-poor households as shown on figure 7, requires an average cutback per unit of $280.13 pesos so their energy expenses share is under the twice the median burden (5.95), this accounts for 1.85 thousand million pesos in total, essential to eradicate energy poverty.

Figure 8. Energy Poverty Gap 2M



Lastly, to pull the households out of the M/2 exp. each household would need to spend in average $85.02 more on internal domestic energy services, implying that the actual energy expenditure is not enough to cover for the basic energy needs, on figure 8 we can see the dotted line which is the actual average energy expenditure $153.61 and the red line representing the required energy expenditure $307.22. The gap ascends to a total of $679 million, the optimal energy expenditure to alleviate energy poverty in accordance with the metric.

Figure 9. Energy Poverty Gap M/2 EXP



A decrease in energy expenditure and energy share is attained by policy action to modify energy tariffs, cutting down costs by targeting the 8.2 million households in energy poverty[13] and creating programmes to support each group considering their specific conditions and demands. Alleviating energy poverty with an interinstitutional strategy, diversifying the energy matrix by driving the spread of renewable energies and the reinforcement of domestic energy convertors upgrading, as well as modifying the construction industry legislation to build energy efficient dwellings and at the same time create programmes to improve the efficiency of old buildings. Still, to boost the energy expenditure from households whose expenditure indicates lacking energy services it is necessary to connect them to the grid, supply modern cooking fuels and provide less harmful and time-consuming domestic technologies, as well as simultaneously raising their income, for example by providing better-paid jobs.

5.4. Logistic regression findings per metric

The empirical evidence suggests the presence of energy poverty in Mexican households, expressed through four diverse metrics. The outcomes reveal connections among them by the similar behaviour of certain indicators, besides, the overall predictability from the regressions is decent; the lowest was from the M/2 exp. with 79.2%, followed by the LIHC with 80.7%, then the predictability from 2M and finally, the highest from the LILC of 89.4%. Due to the diverse nature of the energy poverty metrics, the influence of the variables was inconsistent across the results. Nonetheless, some of the most influential drivers to energy poverty presented a similar behaviour along the metrics, independently of the grade of power and effect on the dependent variable, implying their relevance to Mexican domestic energy poverty. Amongst them drivers, the most influential according to the logits are as follows (See Appendix):

Income (proxy) –Through the LIHC metric, households whose income increase by one thousand pesos have -27% odds of belonging to the energy poverty category, through the LILC the odds reduction is 31.5%. The results suggest that household's income is essential to pull people out of energy poverty. Moreover, the influence of the income variable was more significant for the LIHC and LILC odds of being energy-poor, which can be justified by the composition of this metrics where the data is discerned to exclude higher-income households. The results indicate the need of higher income so that energy expenditure shares become smaller for those whose expenditure is higher, on the other hand, to enable a higher expenditure enough to cover the necessary energy services and simultaneously preventing falling into income poverty.

Location – living in a rural or urban zone is an important driver to energy poverty, the outcomes refer to a positive relationship between an increment on one-unit urban household and that of energy poverty odds from the LIHC and LILC metrics, the odds are 231.4% and 89.9% than those households located in rural areas. This outcome can be explained by the dependency on a centralised energy system, and because of the reduction of cheaper energy options such as firewood and other solid biofuels still available for households located in rural areas. Therefore, although urban households have the benefits of energy supply from the grid

[13] From the total of 8.2 million households adding the results of the four metrics.

and a more extensive matrix of cooking fuels, urban households are trapped into the system having to adapt to the energy prices, being this way, liable to energy poverty.

Fuel for cooking – the use of firewood as a reference variable compared to the odds of other cooking fuels had a diminishing effect for the LILC, similar for the M/2. Moreover, the results for the two metrics measuring higher energy shares, LIHC and 2M, indicate the use of any other fuel than firewood had higher odds of energy poverty membership, for instance, the LPG in 2M had 160.7% more odds and the LPG in LIHC had 51.1% odds than a household using firewood for cooking and food heating purposes. These results are linked to the higher energy expenditure that comes along with the use of more costly fuels, which means that households have access to modern energy fuels and those in energy poverty lack the financial capacity to do so, in other words, their budget limits their energy choices. Equally important, households using freely available energy sources reduce their energy expenses, typically the case for households that are not connected to the grid or living in rural areas.

Electricity Source – electricity can be provided by different sources, the most typical one being the national electricity grid. For the metrics that measure low energy share and expenditure, being connected to the grid has lower odds of -43.5 for the M/2 exp. & -51.2% for the LILC, this is in contrast to households lacking energy access. On this case, connection to the grid will be translated to higher expenditure required to satisfy domestic energy needs, for households whose expenditure is abnormally low due to their lack of energy access. The contrary happens by the 2M and LIHC, in this scenario, being connected to the national grid increases the odds on a factor of 95.7% and 64%, thus, connection to the grid means higher expenditure that can lead to energy poverty.

Additionally, solar panels as electricity source diminish the odds by -89.2% LIHC, -69.4% 2M. Considering the expenditure advantages of solar panels it makes sense that the energy poverty odds of the higher share metrics reduce with one-unit increment of household with solar panels, the results imply a reduction of energy costs by the supply of electricity through the use of this equipment.

Housing tenancy – depending on the tenancy conditions in which households are living there are higher or lower odds of being energy poor; amongst the metrics M/2 exp., LIHC & LILC there is a parallel conduct concerning households where the members have ownership of the housing unit and members who pay a rent, being this of positive nature. In other words, the odds of being M/2 exp. energy poor by renting are 54% higher, similarly, 232% higher by the LIHC and 56.4% higher by the LILC metric than a household who owns their housing unit. This is a typical behaviour for this type of study due to the households' budget choices and the sacrifices that represent the energy share. Many of them pushed to "heat or eat"[9] situations, in this case, it is "have a light or have a roof", where the need to pay dwelling rent aggravates the financial condition of the household, therefore their energy consumption is constrained. Also related is their ability to make modifications to the property to improve its energy efficiency, where tenants are unwilling to invest money on someone else's property, or the owners do not permit users to make any changes.

Energy Price – This variable comprises the electricity prices and LPG prices. The influence of LPG prices on energy poverty is significant, aggravating household's energy scenario increasing the odds by a factor of 21.3% higher for M/2 exp. energy-poor families and 44.5% higher for those on LILC energy poverty. The reaction of Low-income households after energy prices rise, constrained by their low budget, they replace high-priced cooking fuels for cheaper ones, thus, the more expensive the fuel, the smaller the energy expenditure share.

Besides LPG, analogous to the variable "connected to the grid" the electricity price as a driver to energy poverty influences augmenting the odds for a one-unit price increment as reported by the LIHC and 2M, on the other the M/2 exp. and LILC logits reported a reduction of odds by a factor of -32.6% and -12.6% respectively.

Members age composition – The groups of age of the household members are significant drivers to energy poverty, in agreement with the regression's outcome (see appendix) the increment of a member whose age is below 12 years old increases the odds of being energy poor consistently along the metrics. This can be explained by the number of members economically active contributing to the household energy expenses, unlike the higher likelihood by the number of children, who are less expected to contribute to the household budget.

However, an increment of a 65 plus member increases the odds for LIHC and 2M energy poverty, however, it reduces the odds for the M/2 exp. and LILC metrics about an increment of an adult member. This is a situation that can be explained by the simultaneous reduction of energy consumption and the affiliation to poverty and abandonment of the elderly.

Socioeconomic strata – Amongst the four economic strata categories, the most influential in reference to the high strata is its counterpart the low-socioeconomic strata. Conforming to the logit results, households have higher odds of being M/2 exp. energy poor by a factor of 52.3% if they belong to the low strata category, as well as 82.2% higher odds of being LIHC energy-poor belonging to the same strata category. Yet, 2M metric depends on higher energy share making no income distinctions, hence, belonging to the low strata would reduce the odds of being 2M energy-poor by a factor of -56.1%.

Air Conditioner – Having air conditioning influences the odds of experiencing 2M energy poverty by an increment of 118.2%, however, for the rest of the metrics it has the opposite effect by reducing the odds of being LIHC, LILC & M/2 exp. energy poor. If a household is equipped with air conditioning, it is more likely to pay higher electricity bills, and as a result, has a higher expenditure share allocation.

6. Summary of findings

In spite of the general significance of the variables to determine energy poverty, not all of them were as influential. For instance, there are differences in odds between the categories of refrigerator and building age (See Appendix). Another variable that is generally determinant on energy poverty studies of developing countries is the role of gender, although this study does not consider it a powerful driver, it does contribute to some extent.

The logit outcomes tell us about the role of efficient technologies on reducing the household's energy intensity, the relevance of housing policies by the disadvantage of people renting against those who own a dwelling, the integration of social policies and the challenge of protecting vulnerable people by applying instruments that channel the support to reach those who really need it. Typically developing countries household's located in rural areas are most likely to be energy poor, associated with access problems [31], however, the energy phenomenon in urban areas in Latin America is a problem parallel to affordability concerns, intensified by the abandonment of rural life for urban placements. Reducing the energy access problem by moving to urban centres where the grid operates but exacerbating energy poverty through increasing demand and becoming totally dependent on the centralised system [67,68].

Furthermore, the M/2 exp. and 2M metrics can mislead for the households who spend less in energy over their efficient energy system or their possibility to consume more energy due to a less restricted budget [32]. Thus, the LILC metric was included to make a distinction between higher incomes and their capability of being energy efficient, and lower-income households whose expenditure can be under the median as a consequence of other factors. In addition to the LIHC, which accomplishes the same as the LILC except that it does it for the higher expenditure cases.

One of the outcomes from the study is the identification of different energy poverty tiers in line with the metrics applied. First, we found low-income households relying on solid biofuels to compensate for the lack of energy supply, as well as households sacrificing energy services due to the pressure of budget choices. Second, we identified higher income population able to allocate a larger budget to energy, and who are not at risk of becoming income poor by doing so, nor having to switch to inexpensive fuels. And finally, lower-income households who are pushed to make budget choices and opt to allocate a higher share to energy expenditure, which ultimately induces income poverty.

Below-the-threshold energy poverty can be alleviated by filling the gap (As seen in section 5.3) to help households afford their energy bills, thus avoiding other essential budget sacrifices. Above-the-threshold energy poverty can be tackled by reducing the gap, supporting households to spend less of their income on energy and/or increasing their purchasing power. Nevertheless, it is important to emphasise the energy poverty prevalence after affording energy bills, explained by the multiple symptoms and drivers involved. Reducing the gap is not merely a matter of increasing incomes or reducing energy prices, instead, it should be understood as a series of aggregate actions focused on energy needs, services and rights [69].

7. Conclusion and policy implications

The analysis suggests the presence of an energy affordability problem leading to energy poverty in México. Headcounts of approximately 6.9 million households in 2M energy poverty, 7.37 million in LIHC, 8.25 million in M/2 exp. and 3.6 million in LILC energy poverty support this. What is more, a total of 8.2 million households are energy-poor by two of the metrics simultaneously. In Mexico, energy affordability is a rising restriction that impedes households to satisfy their energy needs; providing access to the electricity infrastructure, in other words, being connected to the grid, does not guarantee access to electricity *per se*, therefore, to energy services. A step further is the recognition of the expenditure-based energy poverty rationale by identifying the influence of economic, demographic, geographical and infrastructural variables on the odds of being energy poor.

In agreement to Culver (2017), what we measure matters in energy poverty studies. Hence, in addition to the Mexican energy poverty literature, is the combination and application of several European metrics which added to the accuracy and strength of the results. This study will serve as a base to comprehend the problem and the relevance on distinguishing household's energy demand issues by levels of income, considering location and demographics to create energy support schemes in Latin American countries. Lower-income households should be a priority for energy poverty research and that of energy policy; nevertheless, analysing higher income household's energy behaviour is crucial to generate economic instruments to control their consumption and energy intensity.

Knowing the energy poverty gap could be useful to position energy poor population against those whose expenditure does not lead to energy poverty, picturing the gap not just as the distance from a household and the energy poverty burden but as an inequality breach. Nevertheless bearing in mind that eliminating the expenditure gap does not imply meeting household's energy needs or assuring access to the basic energy services.

The relevance of the study relies on its application to policy generation, aiming for the achievement of sustainable development, energy action and climate change goals, besides the reinforcement of the Mexican energy transition. Since 2013, with the Mexican Energy Reform the government is looking to emulate Europe's energy system liberalisation and a fuel regime change towards renewables, in which it is necessary to integrate the terms 'energy affordability' and 'energy poverty' in addition to the creation of strategies and programmes to strengthen the diffusion of benefits from the transition targeting vulnerable population. Mexico's energy poverty alleviation requires interinstitutional collaboration, building a policy mix amongst the entities involved, conceding the social dimensions of energy as a central role in decision making for a just and equitable transition.

Appendix

Table 1. Variables in the equation from each logit of the metrics: M/2 exp., LIHC, 2M & LILC.

	HEP			LIHC			2M			LILC		
	B	Sig.	Exp(B)	B	Sig.	Exp(B)	B	Sig.	Exp(B)	B	Sig.	Exp(B)
Income	-0.013	0	0.987	-0.315	0	0.73	0.025	0	1.026	-0.378	0	0.69
Average monthly electricity cost per state	-0.394	0	0.674	0.272	0	1.31	0.207	0	1.23	-0.135	0	0.87
index price LPG August 2014	0.193	0	1.213	-0.241	0	0.79	0.15	0	1.162	0.368	0	1.45
Members of the household	-0.004	0	0.996	-0.032	0	0.97	-0.401	0	0.669	-0.047	0	0.95
Members age 11>	0.093	0	1.097	0.079	0	1.08	0.186	0	1.204	0.163	0	1.18
members 65 years +	-0.097	0	0.908	0.117	0	1.12	0.11	0	1.116	-0.175	0	0.84
Energy saving or Incandecent bulbs	-0.129	0	0.879	-0.038	0	0.96	0.188	0	1.206	-0.094	0	0.91
Biodigestion system	0.187	0	1.206	-0.117	0	0.89	-0.162	0	0.851	0.116	0	1.12
Refrigerator 2004-2014 - Reference												
Refrigerator 1994-2004	-0.006	0	0.994	0.093	0	1.1	0.054	0	1.056	-0.146	0	0.86
Refrigerator 1984-1994	-0.606	0	0.546	0.543	0	1.72	0.223	0	1.25	-1.08	0	0.34
Refrigerator 1974-1984	0.134	0	1.143	0.561	0	1.75	-0.441	0	0.644	-0.757	0	0.47
Refrigerator 1964-1974	0.518	0	1.679	-0.793	0	0.45	-0.621	0	0.538	1.062	0	2.89
Refrigerator 1955-1964	-20.3	0.98ns	0	-0.967	0	0.38	-19.82	0.981ns	0	-20.72	0.98ns	0
Refrigerator age: no refrigerator	0.629	0	1.875	-0.209	0	0.81	-0.661	0	0.516	0.392	0	1.48
Building 0-25 years - Reference												
Building age 25 to 50 years	-0.153	0	0.858	0.015	0	1.02	0.148	0	1.16	-0.141	0	0.87
Building age 50 to 75 years	-0.305	0	0.737	-0.083	0	0.92	0.372	0	1.45	-0.011	0.023*	0.99
Building age 75 to 99 years	0.171	0	1.187	-0.296	0	0.74	0.206	0	1.229	0.329	0	1.39
Building age not speficified	0.107	0	1.113	-0.269	0	0.76	-0.082	0	0.921	0.06	0	1.06
A/C system	-0.505	0	0.604	-0.148	0	0.86	0.78	0	2.182	-0.533	0	0.59
Heating system	-0.337	0	0.714	0.436	0	1.55	0.417	0	1.518	-0.767	0	0.46
cylinder or tank for gas	-0.021	0	0.979	0.077	0	1.08	0.036	0	1.036	-0.293	0	0.75
High strata - Reference												
Low socioeconomic strata	0.421	0	1.523	0.6	0	1.82	-0.823	0	0.439	0.127	0	1.14
Medium-low socioeconomic strata	0.161	0	1.175	0.454	0	1.58	-0.681	0	0.506	-0.047	0	0.95
Medium-high socioeconomic strata	0.048	0	1.049	-0.012	0	0.99	-0.373	0	0.689	-0.025	0	0.98
Female or male householder	0.027	0	1.027	0.023	0	1.02	0.096	0	1.1	-0.107	0	0.9
Urban or rural (population size)	-0.194	0	0.824	1.142	0	3.13	0.011	0	1.011	0.642	0	1.9
Own housing unit - Reference												
Renting the housing unit	0.303	0	1.354	1.2	0	3.32	-0.517	0	0.596	0.447	0	1.564
Housing unit is lend	0.056	0	1.057	0.178	0	1.195	-0.356	0	0.701	-0.128	0	0.88
Paying to own housing unit	-0.195	0	0.823	0.872	0	2.392	-0.264	0	0.768	0.162	0	1.176
Housing unit under litigation	0.423	0	1.526	0.022	0	1.022	-0.177	0	0.838	-0.114	0	0.892
Another tenancy situation	-0.038	0	0.962	0.165	0	1.18	-0.153	0	0.858	-0.303	0	0.739
No Access - Reference												
Electricity from private plant	0.021	0.163ns	1.021	-0.505	0	0.604	0.88	0	2.412	0.485	0	1.625
Electricity from solar panels	2.607	0	13.559	-2.222	0	0.108	-1.184	0	0.306	-0.082	0	0.921
Other source of electricity	-0.127	0	0.881	0.44	0	1.552	0.181	0	1.198	-1.153	0	0.316
Electricity from the grid	-0.571	0	0.565	0.495	0	1.64	0.672	0	1.957	-0.718	0	0.488

Firewood - Reference												
Coal	-0.723	0	0.485	0.023	0.001***	1.02	0.652	0	1.92	-0.587	0	0.56
Liquid petroleum domestic gas	-1.242	0	0.289	0.412	0	1.51	0.958	0	2.607	-1.149	0	0.32
Natural Domestic gas	-1.979	0	0.138	0.098	0	1.1	0.785	0	2.193	-1.74	0	0.18
Electricity	0.138	0	1.148	-0.828	0	0.44	-0.203	0	0.816	-0.158	0	0.85
Another type of fuel	0.128	0	1.137	-0.536	0	0.59	-0.358	0	0.699	-0.685	0	0.5
Solar powered water heater	0.164	0	1.178	0.168	0	1.18	-0.024	0	0.976	-0.164	0	0.85
No water heater	0.052	0	1.053	-0.025	0	0.98	0.161	0	1.174	0.064	0	1.07
Constant	1.207	0	3.344	0.137	0	1.15	-5.433	0	0.004	-2	0	0.14

Levels of significance are indicated by an asterisk: * represents significance of P<.05, ** represents significance of P<.01, *** represents significance of P<.001, “ns” represents a non-significant coefficient.

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