Measuring energy poverty in South Africa based on household required energy consumption

Yuxiang Ye*, Steven F. Koch

Department of Economics, University of Pretoria, Republic of South Africa

Abstract

This study incorporates household energy needs into Foster-Greer-Thorbecke (FGT) based poverty measures to examine energy poverty in South Africa. Our household-specific energy poverty line is founded on the application of semiparametric estimation of energy expenditure shares that are used to determine a household energy equivalence scale and, thus, the household specific required energy consumption level or poverty line. We find that headcount energy poverty is extensive, exceeding 50%, as is the gap and the severity of energy poverty. Decomposition results suggest that energy poverty rates decrease with income, and lower income groups contribute more to total poverty than higher income groups across all the three poverty indexes. Although our poverty rates are determined by the choices we have made, the model is flexible enough to allow for assumptions that differ from ours, and we provide a useful sensitivity analysis for further understanding.

JEL classification: Q40, Q41, Q42, Q48

Keywords:

Energy poverty, Required energy consumption, Foster-Greer-Thorbecke poverty measures, Developing country

*Corresponding author. Send correspondence to Department of Economics, University of Pretoria, Private Bag X20, Hatfield, Pretoria 0028, Republic of South Africa. E-mail addresses: yuxiang.ye2011@gmail.com (Y. Ye), steve.koch@up.ac.za (S.F. Koch). This research did not receive any direct grant from funding agencies in the public, commercial, or not-for-profit sectors.

1. Introduction

In this study, we apply Foster-Greer-Thorbecke (FGT) measures (Foster et al., 1984) to examine energy poverty in a developing, but somewhat energy advanced context, South Africa. FGT measures provide information on the incidence of poverty (headcount index), while allowing a deeper investigation of the consumption distribution within the poor (severity index). The severity index satisfies two fundamental properties of poverty measures: monotonicity and transfer axioms (Sen, 1976; Foster et al., 1984). More importantly, it has an additional advantage from an empirical point of view - it is additively decomposable - which allows for a more nuanced understanding than might be available at the aggregate level. The relative severity of energy deprivation among households could be of interest to policy makers, because it can suggest targeted interventions. We exploit that thinking in our analysis, as well, to see if an extension of the current free basic electricity (FBE) program in the country, discussed below, has the potential to mitigate energy poverty and severity.

Our primary contribution is to incorporate household energy needs/requirements into FGT-based energy poverty measurement. As is well known, FGT measures require a poverty line. Specifically, we estimate household energy need, which is conceptually similar to an energy poverty line. Despite the potential benefits associated with measuring energy poverty based on energy need, a clear and simple to apply definition of household energy *need* (e.g., theoretical or modelled energy consumption) remains a stumbling block in many settings. In application, actual energy expenditure is often used instead of required expenditure (Herrero, 2017; Romero et al., 2018; Mohr, 2018). However, as argued by Moore (2012), "actual fuel spending is a poor indicator of energy poverty". Actual expenditure may underestimate energy poverty, especially for low-income households, because vulnerable households are likely to constrain their energy consumption, so they can afford other pressing needs (Papada and Kaliampakos, 2020; Churchill et al., 2020). That concern could be especially relevant in low- and middle income developing countries.

We are not the first to use FGT to examine energy poverty, although we do offer a unique and household-specific poverty line. Foster et al. (2000) apply a poverty line based on average energy consumption for households whose overall per capita consumption level falls at or below the income poverty line of the country. Like ours, their energy poverty line is easy to adapt and calculate from income and expenditure survey data; however, it is based on the assumption that energy poor households are also income poor (Khandker et al., 2012), and, therefore, it potentially conflates energy poverty and income poverty. Pereira et al. (2011) develop a poverty line from the estimated minimum energy consumption (in Gj/year) for residential cooking, heating and lighting in the area; however, their data is drawn from fieldwork in a particular area of rural Brazil, and, therefore, may not be easy to adapt to other locations or may be expensive to replicate for comparative purposes. Heindl (2015), on the other hand, determines a poverty line from the 10% indicator (Boardman, 1991) in Germany, but it is limited to households with income below the median, which may also conflate energy and income poverty and does not necessarily adjust appropriately for need, due to the use of actual expenditure in the calculation. Similarly, Simshauser (2021) use the 10% indicator for low income households in Australia, while Legendre and Ricci (2015) assess the extent of income poverty for the most fuel vulnerable households in France, which is, thus, rather different from our interest.

An important advantage of our method is that it offers a household-specific poverty line. A single fixed energy poverty line applicable to all groups may not be appropriate (Greer and Thorbecke, 1986), because households differ in size, composition and other characteristics. Therefore, they are likely to have different needs, even though domestic energy consumption has household public good characteristics (Lazear and Michael, 1980; Nelson, 1988). Thus, our FGT analysis uses household-dependent energy poverty lines, such that a household is defined to be energy poor if it does not purchase the energy it *needs*. Because our method is based on expenditure survey data, which is collected in most every country, it can be fairly easily adapted to the relevant country circumstances, and, therefore, used for cross-country or within-country dynamic comparisons.

Our analysis is underpinned by an updated version of the semiparametric equivalence scale method proposed by Ye et al. (2020). To estimate need, the approach needs to account for household differences. Although the model is flexible enough to account for more, depending on the data that is available, we focus on differences in household composition, weather and electric appliance ownership. Methodologically, the household's need (or energy poverty line) is derived from an equivalence scale adjustment of a reference energy requirement. That reference incorporates a specific type of household and level of energy expenditure meant to capture a reasonable living standard in South Africa. As a result, the household poverty line depends crucially upon the reference choices, because they underpin any adjustment.

Our results suggest that at reasonable reference levels, at least half of the sampled South African households are energy poor, although the energy poverty severity index is lower. However, because these results are dependent on reference choices, we present sensitivity analysis based on different reference choices. We also compare our results to previous research in the country, which offers some validation of our approach. Finally, we decompose energy poverty across income groups, finding that average energy poverty rates tend to decrease with income for all the three indexes. As might be expected, the percentage contribution that lower income groups make to the total is more than that of higher income groups.

2. Literature review

2.1. Energy poverty

In 2019, about 759 million people could not access electricity, nearly 75% of them (570 million) from Sub-Saharan Africa, which represents more than half of the region's population (IEA et al., 2021). Binary indicators of household access to electricity, such as the preceding, are easy to understand and are often used to describe energy poverty, the situation wherein household basic energy needs cannot be met. However, binary indicators do not capture the full extent of energy poverty.[1] For instance, some households have access to, but are not able to afford electricity (Winkler et al., 2011; Ye et al., 2018; Zhang et al., 2019), and, therefore, mixed energy use is quite common. As IEA et al. (2021) reports, about one-third of the world's population lacks access to clean cooking fuels and most of those are living in developing Asia and sub-Saharan Africa.[2] Thus, an indicator of access to modern energy services will mask the complexity of domestic energy use.

To address some aspects of this complexity, multidimensional measures that consider a set of binary indicators have been proposed and widely used. For instance, Pachauri et al. (2004) propose a two-dimensional measure of energy poverty in India, which covers energy access and the quantity of energy consumed. A focus on three deprivation dimensions – monetary poverty, residential energy efficiency and heating constraints – may offer a reprieve in complexity (Charlier and Legendre, 2019). However, this has only been used to measure energy poverty in developed countries, especially in Europe. Further, it requires information on both relative energy efficiency, which may not be widely available in developed countries, and heating constraints, which may be of limited relevance in many developing country contexts, where temperatures are rarely cold.

Following Alkire and Foster (2011), Nussbaumer et al. (2012) develop a multidimensional energy poverty index (MEPI) focusing on access deprivation with respect to modern energy services. The MEPI incorporates diverse dimensions related to residential energy consumption. However, the results could be limited by the selection of dimen-

[1] In the literature, *energy poverty* is widely used to emphasize the lack of access to modern energy services in developing countries (Li et al., 2014), although in some instances it is also applied in developed country studies (e.g. Okushima, 2017; Kyprianou et al., 2019; Robinson, 2019; Bednar and Reames, 2020). *Fuel poverty* tends to refer to the affordability of energy in developed countries, especially in Europe (e.g. Boardman, 1991; Liddell et al., 2012; Legendre and Ricci, 2015; Heindl, 2015; Thomson et al., 2016), and the US (Mohr, 2018). *Energy insecurity* is also often used to describe the similar situation in the US (Hernández, 2016; Memmott et al., 2021). In this paper, we talk about *energy poverty* as it covers both the lack of access to modern energy services and the lack of affordability of energy services.

[2] Clean fuels and technologies refer to electricity, liquefied petroleum gas (LPG), natural gas, biogas, solar, and alcohol fuel stoves according to the 2014 World Health Organization (WHO) guidelines for indoor air pollution from household fuel combustion (IEA et al., 2021).

sions of interest and affected by the assignment of different weights for each dimension. The World Bank's multi-tier framework (MTF) to measure energy access (Bhatia and Angelou, 2015) improves on the previous binary or even multidimensional indicators of energy access. However, it is also complex, and may be difficult for global tracking purposes (Pachauri and Rao, 2020), due to an intensive data requirement, as well as its sensitivity to decisions in its design (Mendoza Jr et al., 2019).

Rather than a focus on access or related binary and multidimensional indexes, one could try to incorporate all aspects of energy consumption. Domestic energy consumption expenditure captures all energy usage and is a component of total household expenditure (Welsch and Biermann, 2017). Thus, energy expenditure-based approaches, where we place our methods, could describe energy affordability via the relationship between what a household *needs to spend* on energy and the household's total income or expenditure (Heindl and Schüssler, 2015; Deller, 2018; Churchill and Smyth, 2020). For instance, the 10% indicator (Boardman, 1991) defines energy affordability as a ratio - the ratio between required household energy expenditure and total household income, such that a household is energy poor if it *needs to spend* more than 10% of its income on energy consumption. The required energy concept implies that actual energy consumption may not be enough, because low-income households may restrain their energy consumption if other consumption needs have to be met first. However, this indicator is open to a few criticisms. Implicitly, such a ratio is underscored by a measure of energy need, which is not widely available. The 10% threshold relies on observations made many years ago, when it was about twice the median energy expenditure share of income in 1988 in the United Kingdom (UK) (Liddell et al., 2012). Also, it does not exclude high-income households, such that some high-income households with high energy shares are classified as energy poor, which led to the after fuel costs poverty (AFCP) indicator (Hills, 2011).

The AFCP approach defines a household as energy poor if its equivalised income is less than 60% of the equivalised median income, where income should be net of housing costs (mortgage payments or rent) and household required energy. The advantage of this indicator is that it incorporates housing costs. Deducting housing costs from household income provides a truer picture of a household's disposable income (Hills, 2011; Herrero, 2017). The AFCP indicator identifies income poor households whose situation is worsened by high energy expenditure, such that nearly all low-income households could be classified as energy poor, regardless of their energy requirements. Hence, it may not offer a clear separation between income poverty and energy poverty (Legendre and Ricci, 2015). The low income high costs (LIHC) indicator (Hills, 2012), which focuses on households with both low income and high energy expenditure, is likely better.

The LIHC indicator requires two thresholds: the energy cost threshold and the income threshold. The energy cost threshold is the equivalised median required energy spending over all households, and therefore, it is the same for all households. The income threshold is set at 60% of equivalised median (net of housing costs) income for the whole sample, plus the equivalised required energy expenditure of that household. The income threshold varies by household, depending on the required energy expenditure of the household. Although LIHC focuses on the overlap between low incomes and high required energy spending, there are a few potential shortcomings: (1) as its default, the income non-poor cannot be energy poor; (2) it is not able to capture some vulnerable households who were pushed into income poverty due to their expenses on energy consumption (Legendre and Ricci, 2015); (3) it is not transparent about the estimation of equivalence factors for energy expenditure (Moore, 2012).

Similarly, a minimum income standard (MIS) indicator is built upon a minimum income standard for Britain (Bradshaw et al., 2008), which is defined as "having what you need in order to have the opportunities and choices necessary to participate in society". Based on this concept, Moore (2012) defines a household as energy poor if it has insufficient residual net income to satisfy its energy requirements, after deducting actual housing costs and all other minimum living costs (defined as MIS). The MIS indicator focuses a spotlight on the income available for energy needs after the basic needs have been met. It is a relative definition, which would be adaptable to other countries with different incomes and standards of living (Moore, 2012). It also takes account of housing costs and household energy requirements, although required energy consumption is not widely available.

There is no consensus on the amount of required energy to satisfy human basic needs (Pachauri and Spreng, 2004). The assessment of a minimum requirement of physical energy is normally based on engineering methods and requires extensive residential energy usage data (Parikh, 1978; Bravo et al., 1983; Krugmann and Goldemberg, 1983). However, detailed engineering models that properly account for the range of fuels used to produce household energy may not be plausible in developing countries. Household energy requirements vary with climates and regions, as does housing energy efficiency (Charlier and Legendre, 2019; Charlier et al., 2019), while engineering method estimates depend on assumptions about minimum energy needs (Khandker et al., 2012).

Alternatively, Barnes et al. (2011) propose a regression approach to determine residential minimum energy needs controlling for household and community characteristics using data from a household survey of rural energy use in Bangladesh. Barnes et al.'s (2011) estimated energy requirements may better fit specific contexts, as they consider local specificities and country differences (Jiang et al., 2020). However, detailed price data across energy sources can be difficult to access in many contexts, including ours, therefore, the method may not be as widely applicable, as needed. In addition, Chidebell-Emordi (2015) propose a minimum energy poverty line using field research in urban Nigeria; such an analysis may not be easily generalised to a wider population, even within a country. In our study, we follow an alternative that does not require price data, but is conceptually similar to the above-mentioned regression approaches. Our approach uses publicly available household budget survey data.

2.2. South Africa

South Africa's electrification rate reached 85% in 2019, due to the national electrification programme started in the 1990s (Winkler et al., 2011; Essex and de Groot, 2019); for rural areas, the percentage of the population with access increased to 79%, up from 24%

in 1996.[3] As a result of the national roll-out, electricity from the grid has become the major source of energy for lighting (87,2%), water heating (82,5%), cooking (81,3%) and space heating (38%) in the residential sector (Stats SA, 2019). While the sector's consumption of electricity accounted for 72% of the total energy consumed in the residential department in 2016 (DOE, 2019).

Despite the increase in electrification rates, it is evident that fuelwood still has been widely used for thermal purposes by South African households, especially for cooking (Guild and Shackleton, 2018; Uhunamure et al., 2017; Madubansi and Shackleton, 2006). Our analysis, below, as well as other recent research (Bohlmann and Inglesi-Lotz, 2018), corroborates the finding that low-income South African households continue to use various sources of energy, including wood and paraffin, to satisfy their energy requirements. The prevalence of multiple energy sources must be incorporated into any analysis of the residential sector's energy demand and/or requirements.

For the households in poor urban and peri-urban areas, the ability to afford the electricity rather than access to the service is the main problem (Visagie, 2008). Affordability is not expected to have improved, primarily because of the rapid rise in electricity prices. From 2008 to 2018, the state utility's, Eskom's, annual average domestic electricity price has increased by more than 120% (DOE, 2018), while South Africa's average consumer price index (CPI) has increased by approximately 70% over this period (Stats SA, 2021a). The high electricity price has resulted in an increased energy (cost) burden and influenced household decision-making with regard to energy choices. As indicated by Ye et al. (2018), the electricity price is one of the key determinants of domestic energy demand in South Africa. Bohlmann and Inglesi-Lotz (2020) conclude that electricity prices have a significant impact on electricity demand for all South African households at low-, middle- and high-income levels. In terms of one measure of affordability, DOE (2013) finds that approximately 43% of South African households spend more than 10% of their budget on domestic energy services. Moreover, they find that some grid-connected households

[3]The World Bank; see `https://data.worldbank.org/country/south-africa` [accessed at 2021-6-17].

use substitute fuels to meet their energy needs.

Not all of these substitutions are necessarily bad. For instance, some households may switch to other cheaper modern energy sources like liquefied petroleum gas (LPG) or solar, the latter of which is often used for water heating. As shown in Figure 1, the percentage of households using LPG for cooking follows an upward trend from 2002 to 2018, while the usage of wood and paraffin has decreased simultaneously over those years. For lower income groups, their energy choices are limited. They may have to switch to traditional and/or transitional fuels due to budget limitations. As summarised by DOE (2013), unaffordable electricity consumption results in mixed energy usage patterns across all income groups, although that is likely to be a bigger problem amongst poorer households.

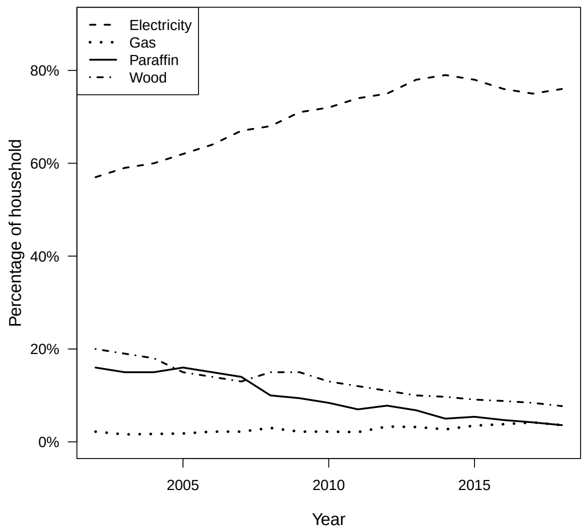

Figure 1: Percentage distribution of main energy sources used for cooking, 2002-2018.[4]

Although there is prevalent income poverty in South Africa (Leibbrandt et al., 2016), direct and indirect government projects have been implemented to eliminate energy

[4]Source: Stats SA (2019).

poverty (Balmer, 2007), one such programme is the free basic electricity (FBE) policy (DME, 2003). The policy provides free electricity to poor households connected to the national grid in order to support them in meeting their basic energy needs. The initial FBE was set to 50 kWh per household per month, subject to registration in the indigent programme and installation of a prepaid meter. However, its implementation has not been consistent across municipalities in terms of the FBE level (Ye et al., 2018). In 2019, more than 80% of South Africa's municipalities provided this basic service, and more than 10% of South African households received FBE according to the number reported in Stats SA (2021b).[5]

In addition to FBE, a free basic alternative energy (FBAE) policy was launched by the government in 2007 aiming to facilitate the provision of basic energy needs to indigent South African households that do not have access to electricity (DME, 2007). The alternatives to electricity include paraffin, LPG, coal, fire gel and solar home systems, for example. In 2019, more than 1% of South African households received this FBAE service, among which 70% have been provided with solar home systems by the municipalities (Stats SA, 2021b). The provision of certain amounts of free electricity or alternative energy offers poor households not only the opportunity to meet their basic energy needs, but it also potentially affects their energy choices and spending on energy.

Davis et al. (2008) investigate the impact of FBE on the energy choices of low-income households in South Africa using data from pre- and post-FBE surveys in two rural villages. Their results suggest significant increases in energy consumption after introduction of FBE in one village, which may be due to an increase in electric stove ownership rates. Although the policy is not expected to affect income levels, Mvondo (2010) shows that the FBE policy has limited effects on family income in Buffalo city

[5]According to Stats SA (2021b), 1.8 million South African households received FBE, which is about half of the municipality-identified indigent households in 2019. While an indigent household is a poor household, as determined by municipalities, and the mechanism for identification of such households can vary across municipalities. For example, a number of municipalities used monthly income cut-off points to identify indigent households in 2019 (Stats SA, 2021b). In addition, it is estimated that there are about 17.16 million households in South Africa in 2019 (Stats SA, 2020), hence, roughly there are 10% households received FBE service (1.8/17.16 = 10.5%).

municipality - one metropolitan municipality in South Africa. However, there are no estimates of the impact FBE may have in alleviating energy poverty. Admittedly, the effect might not be extensive. For instance, Masekameni et al. (2018) find limited access to FBE for households in some areas and many households that are not aware of the tariff relief programme. This situation has been improving from 2020, because Eskom and municipalities continue to urge approved indigent households to claim their FBE, in order to support energy needs during national lockdowns put in place due to COVID-19. Mvondo (2010) indicates that 50 kWh of FBE is insufficient for indigents to meet their basic energy needs; only 9% of the indigent households are able to live within the the FBE limit and would need to purchase extra electricity. The rest either pay for additional electricity or connect to the grid illegally. In addition, Mvondo's (2010) research suggests a strong relationship between household electricity consumption and household size; small families consume low levels of electricity, while large households, on average, make extensive use of illegal electricity.

In South Africa, a number of recent papers consider the breadth and depth of energy poverty. We summarise that literature in Table 1. As can be seen from the summary, the local literature explores energy poverty from an access or affordability perspective via unidimensional or multidimensional measures, although the DOE (2012, 2013) assesses energy poverty through a subjective self-reported measure, supplemented with qualitative surveys/interviews. DOE (2012, 2013) measure affordability via actual energy expenditure, instead of required expenditure for the 10% indicator, while the 10% threshold has been taken without further clarification. As indicated by Charlier and Legendre (2019), the 10% indicator is not expected to be suitable for policy making, because of its outdated and country-specific threshold of energy expenditure. Vermaak et al. (2014), on the other hand, consider household minimum energy needs using the IEA's (2009) three levels of energy requirement as their energy poverty line. Our approach offers a wider set of energy poverty measures, and is underpinned by the most recent available data. Thus, we are able to provide more recent and nuanced results to complement previous findings.

Table 1: Energy poverty measurement literature in South Africa.

Source	Data and period	Measurement and indicators	Results
DOE (2012, 2013)	Data from the Energy-related Behaviour and Perceptions Survey in 2012 and 2013	1) Affordability: 10% indicator	2012: 47%; 2013: 43%
		2) Subjective approach	2012: 43%; 2013: 39%
		3) Low-income and thermal inefficiency[a]	2012: 22%; 2013: 26%
Vermaak et al. (2014)	2008/2009 Department of Energy Survey on the Socioeconomic Impact of Electrification	Using the amount of useful energy as threshold to determine energy poor	23%-69%
Ismail and Khembo (2015)	The National Income Dynamics Study (NIDS) data wave 3 from 2012	Affordability: 10% indicator	25%
Tait (2017)	Own survey in two poor communities in Cape Town	Multidimensional energy poverty index (MEPI): electricity access and fuel usage, affordability, safety and reliability	55%-96%
Israel-Akinbo et al. (2018)	Low-income households from the NIDS data wave 1 from 2008, wave 2 from 2010, wave 3 from 2012 and wave 4 from 2014	MEPI: modern energy lighting, modern cooking fuel, basic appliance ownership,entertainment/education appliance ownership, and modern heating fuel	2008: urban 38%, rural 62%; 2010: urban 37%, rural 61%; 2012: urban 41%, rural 59%; 2014: urban 41%, rural 59%
Mbewe (2018)	The NIDS data wave 1 form 2008 and wave 4 from 2014	1) Affordability: 10% indicator	2008: 21%; 2014: 13%
		2) MEPI: modern cooking fuel, electricity access, household appliance ownership, education/entertainment appliance ownership, telecommunication devices	2008: 37%; 2014: 19%
Ningi et al. (2020)	Survey data from two coastal communities in rural Eastern Cape in South Africa	Multidimensional: access to electricity, access to an electric stove, access to additional measures of energy (paraffin, gas, crop residue, and cow dung)	16% - 17%

[a]: Low-income and thermal inefficiency approach: a household is considered as energy poor if it has less than 60% of South Africa's median per capita monthly income and dissatisfied accommodation in terms of thermal efficiency (DOE, 2012, 2013).

3. Methods

3.1. FGT measures

The Foster-Greer-Thorbecke (FGT) class of poverty measures proposed by Foster et al. (1984) have been widely applied in the assessment of incidence, gap and severity of poverty (Foster et al., 2010). In this study, we apply the standard FGT formula to energy poverty:

$$P_\alpha = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{(z_i - y_i) \times \mathbb{I}(z_i > y_i)}{z_i}\right)^\alpha, \ \alpha \geq 0, \tag{1}$$

where N is the total number of households, z_i is the household-specific energy poverty line and y_i is household i's actual energy expenditure. $\mathbb{I}(\cdot)$ is an indicator function which equals 1 if $z_i > y_i$, otherwise, it is 0. α is the sensitivity parameter; as the value of α increases, the FGT measures give more weight to the distribution of energy expenditure at the lower end.

In this study we set $\alpha = 0, 1$ and 2, respectively, in measuring the incidence, gap and severity of energy poverty in South Africa. Specifically, for $\alpha = 0$, P_0 is the standard headcount ratio, i.e., the proportion of households that are below the energy poverty line. Although easily counted, the headcount ratio does not consider the intensity of poverty, nor does it indicate how poor the poor are, such that it does not change if households below the poverty line become poorer (Haughton and Khandker, 2009). For $\alpha = 1$, P_1 is the poverty gap index, which measures the normalized gap between the average energy expenditure of the poor households and the poverty line. This indicator, however, does not reflect changes in the distribution of energy expenditure among the energy poor households. For example, a transfer of some amount of energy consumption from the poorest household to the next poorest household would have no effect on the poverty gap rate. Further, it does not take the inequality among the poor into consideration. Thus, when calculating the energy poverty gap it gives the same weight to those who are just below and far below the poverty line. For $\alpha = 2$, P_2 is the energy poverty severity index (the square poverty gap); it puts higher weight on poorer households. The severity index is a weighted sum of poverty gaps, as a proportion of the poverty line, where the weights are the proportionate poverty gaps, themselves. Hence, by squaring the energy poverty gap index, the measure implicitly places more weight on observations that fall far below the energy poverty line than those that are closer to it.

Although a one-size-fits-all poverty line is common, energy poverty levels should reflect real differences in need accounting for variations in the size, composition and other relevant characteristics of the household.[6] In other words, a fixed energy poverty line could ignore heterogeneity across households.

3.2. Energy poverty line

We base the poverty line on household required energy consumption, updating the equivalence scale method proposed by Ye et al. (2020). Intuitively, the method estimates adjustment factors, which are then used to rescale a reference measure of required energy expenditure to determine the energy requirements for that household. The adjustment factors account for differences in household structure, average weather, appliance ownership and dwelling size and are estimated semiparametrically; the method is general and can incorporate numerous control variables to match the local situation.

Thus, the energy poverty line is derived from a reference group's energy requirement, rescaled by a household-specific adjustment factor, as in

$$z_i = \bar{E} \times \Lambda_i, \tag{2}$$

where z_i is household i's energy poverty line (i.e. required energy consumption) in Equation (1), $\bar{E}$ is the reference energy requirement, and Λ_i represents the energy equivalence adjustment factor for household i. This reference level depends crucially on the level of expenditure chosen and, to a lesser extent, the underlying features of the reference household, because the empirical analysis accounts for feature differences between households.

[6]Hills (2011) defines an energy poverty gap as the difference between the energy poverty line and household required energy consumption, which is similar to the FGT gap measure. As with Foster et al. (2000), their energy poverty line is fixed; it is the median of modelled household energy bills.

The reference group's energy requirement ($\bar{E}$) is taken from the distribution of the reference group's energy expenditure, where the reference group is meant to capture a reasonable living standard in South Africa. We assume that a reasonable standard of living requires access to or use of electricity, living in a formal urban area, modern energy sources for cooking, as well as cold storage for food, the ability to communicate and be entertained. The approach is easily generalisable, depending on the sort of data that is available, as well as the assumptions one makes with regard to living standards. Along with these living standards assumptions, the methodology accounts for the age and composition of household members, and, therefore, the analysis requires the specification of reference household size and composition. Thus, we define a reference household to be a single (adult) person living in own property with a medium space (between 30 and 59 m^2) in spring or fall, having a refrigerator or freezer, cooking with modern energy sources, being able to communicate with a cellphone and able to access entertainment through at least a television (TV), radio or satellite TV. We do not require geysers (electric water heaters) in our reference households, due to the fact that piped water access for each dwelling is often a luxury, as well as the fact that hot water may not be provided through individual geysers, especially in apartment buildings. To investigate whether receiving free electricity has impact on energy needs, we further limit the reference to be the ones not reporting positive FBE values.

The final component of the reference level is the choice of expenditure to use from the reference group. For the analysis, we chose the 75^{th} percentile of the distribution of reference household energy consumption. Our choice is driven by two features of the data that can be seen in Tables 2 and 4. Our first observation is that energy expenditure is skewed by income (proxied by total expenditure) – mean energy expenditure per income decile increases consistently by about ZAR 25 per month until decile seven to eight; see Table 2. Thus, the 75^{th} percentile represents a salient point of behaviour separation between income and energy expenditure. Specifically, it suggests that households at that position in the income distribution may no longer be constrained in their electricity purchases. Our second observation is that the 75^{th} percentile of energy expenditure for the reference sample (ZAR 231.10 in Panel A of Table 4) is close to the mean energy expenditure in the seventh income decile (ZAR 270.46 in Table 2). As this percentile and resulting reference expenditure might be contentious, we undertake sensitivity analysis using other points in the reference energy expenditure distribution for comparison.

To estimate the energy equivalence scale (Λ_i), a semiparametric model over household energy expenditure shares is applied. A similar model was initially proposed by Yatchew et al. (2003), and it imposes base-independence (Blundell and Lewbel, 1991; Blackorby and Donaldson, 1993; Pendakur, 1999). Explicitly, base-independence implies that Engel curves are non-linear in the log of expenditure and are vertical and/or horizontal translations of each other. In addition to base-independence, Ye et al. (2020) incorporate a wide range of additional controls for the aforementioned household attributes, as in

$$
\begin{aligned}
w(x^r, \mathbf{d}^r) &= w\left(\frac{x^i}{\Lambda_i(\mathbf{d}^i)}\right) + \varepsilon \\
&= f\left(\ln x^i - \sum_j \lambda_j d_j^i\right) + \varepsilon,
\end{aligned}
\tag{3}
$$

where w denotes household energy share, x is total household expenditure, vector $\mathbf{d}$ represents categorical characteristics related to household basic energy needs, superscript r refers to the reference household, and superscript i refers to a non-reference household.[7] Λ_i is the energy equivalence scale to be estimated for household i, d_j^i denotes non-reference household i's categorical characteristic j with a value of either 1 or 0, λ_j is the coefficient for characteristic j in the semiparametric model, and ε is the error term assumed to not be correlated with the other variables in the model.[8]

[7] Characteristics are indicators, such as having a fridge or a specific number of adults or children in the household. The full set of variables and results are presented in Table B.2. The reference household, by definition, is the reference household in this regression.

[8] In results not reported, we also allow for correlation, following a nonparametric control function approach (Dong, 2010). Identification is underscored by a continuous control variable that may or may not be an instrument, in the normal sense. The results, available from the authors, point to statistically significant endogeneity, which reduces the energy requirements for richer households; however, overall endogeneity has little impact on what is reported below.

The function f, a convolution of the reference group's budget share function w with the exponential function, is estimated nonparametrically, via the np package (Hayfield and Racine, 2008) for R (R Core Team, 2021). With the log-linear index model within f, we are able to calculate the equivalence scales from the exponentiation of the estimates. In our analysis, the scales have been adjusting for multiple household characteristics, therefore, it is necessary to take the exponential of the sum of the estimates for all of the relevant characteristics (that are different from the reference household). That is,

$$\Lambda_i(\mathbf{d}^i) = \exp\left(-\sum_j \lambda_j d_j^i\right). \tag{4}$$

4. Data

The data used for this study come from the South African Living Conditions Survey (LCS) 2014/2015 (Stats SA, 2017a). Although one could undertake a similar analysis using a panel that is available in South Africa, the National Income Dynamics Study (NIDS), we use the LCS because it is similar to household budget surveys conducted around the world, and it contains household-level information related to free basic electricity, which is not available in NIDS. The LCS 2014/2015 datasets include detailed information on household expenditure, energy expenditure and a number of household-level characteristics for 23 380 households. In terms of domestic energy consumption, the LCS survey captured spending on a number of household fuels including electricity (conventional metering, prepaid and free basic electricity), gas (refilling gas and gas in cylinders), liquid fuels (paraffin, petrol and diesel for household use, not transport use), solid fuels (bought and fetched firewood, charcoal, candles, coal, bought and fetched dung, and crop waste), and other household fuel.[9] In our analysis, total energy expenditure

[9]The value of free basic electricity refers to the monetary value of the amount of electricity received. In the survey, this value was provided by the respondents and it is mostly reported by those households who are registered as indigents in their municipalities. For those households whose value of free electricity appeared in their utility bill it's the one that they reported. In addition, electricity theft through illegal connections, tampering and bypassing of electricity meters has been a serious issue in South Africa, which results in an amount of 3730 GWh to 5968 GWh loss (between 1.57% and 2.52% of total energy

includes expenditure or market values from all of these energy sources. Unfortunately, some households have consolidated water and electricity bills, which cannot be separated, while some households' rental includes electricity, such that they are not responsible for their electricity expenditure. Therefore, those households are ignored in our analysis.

We further limit the data to households with no more than seven adults and no more than five children, primarily because larger households are quite rare. We also drop observations missing information related to domestic appliances (refrigerator, freezer, cellphone, TV, radio, satellite TV and geyser), the main energy source for cooking and living space (estimated area of the dwelling). Finally, we remove any others whose energy expenditure cannot be separately determined, such as households, primarily individuals, who are borders and households that do not purchase any form of energy. Our analysis sample, therefore, includes 17166 observations from the initial 23 380. To see if dropping those observations affects the representativity of the empirical analysis, we compare the mean of selected variables in our regression for both the retained and dropped samples (Table A.1). There are but a few differences. For example, *renter* accounts for 56% of the dropped sample as opposed to 14% of the retained, which also relates to the relatively higher proportion of *urban formal* dwellings in the dropped data (64% v 50%), the greater proportion of FBE in the retained sample (14% v 6%) and the differences in the space data. In the data, renters are relatively more likely to have their electricity be part and parcel of their rental payment, and, especially those in apartment complexes, are more likely to live in cities. It is also less likely that an indigent household will be in a position to sign a rental agreement, and, therefore, FBE is understandably lower within the dropped sample. Finally, the space information for renters was not captured as fully as it was for the rest of the households; we discuss this more fully, below. Thus, although there is some evidence of selection in our sample choices, it is does not appear to be extensive, and, therefore, may not influence the generality of our conclusions.

In the analysis, household consumption expenditure is used instead of income for all

sent out) in 2015 (Eskom, 2015). Unfortunately, it is not possible to include such information in our empirical analysis due to data availability.

the estimates. In developing countries, formal employment is less common, such that many households have multiple and continually changing sources of income. Furthermore, home production is more widespread, and, therefore, expenditure is expected to be smoother than income (Deaton and Grosh, 2000). In addition, all reported expenditures were inflated/deflated to April 2015 (the midpoint of the survey year) using the CPI, because the LCS was collected over the period of a year.

Table 2 describes some of our data across expenditure groups. An average household spends about 7% of its budget on energy, while average total expenditure in the household is ZAR 7 465 per month (≈USD 622; 1 USD ≈ 11.997 ZAR in April 2015). As expected, there are differences across expenditure groups. In particular, the average energy share decreases with total expenditure, but lies between 3% and 14%. We further examine these shares to gauge the proportion of households in each expenditure group that spend more than 10% of their budgets on energy. In total, this figure is near 20% in the country, and the proportion of households exceeding this threshold falls as total expenditure increases. Worryingly, amongst the lowest expenditure decile, the figure exceeds 60%. As noted above, it is possible that these households are curbing their energy consumption in order to meet other priorities, and, therefore, 60% is likely to be a lower bound.

Table 2: Descriptive statistics by expenditure group ($N = 17166$).

Expenditure decile	Energy expenditure (ZAR)	Total expenditure (ZAR)	Energy share	Energy share > 10%
1(lower)	114.61	896.01	0.14	0.64
2	139.60	1485.84	0.09	0.31
3	159.21	1985.03	0.08	0.23
4	175.38	2530.38	0.07	0.18
5	201.83	3187.98	0.06	0.14
6	234.10	4067.99	0.06	0.12
7	270.46	5374.21	0.05	0.08
8	359.55	7677.79	0.05	0.06
9	504.80	12873.70	0.04	0.04
10(upper)	843.78	34589.97	0.03	0.01
Total	300.29	7465.10	0.07	0.18

Household energy expenditure and total expenditure are monthly values. Energy share is calculated as the ratio between household energy expenditure and total expenditure.

The summary statistics for the data used to estimate Equation (3), and, thus, the equivalence adjustment in Equation (4), and, finally, the energy poverty line in Equation (2), is available in Table 3. One of the main features that we examine is the effect of household size and the number of children and adults – through binary values of these variables.[10] We see that more than 45% of South African households have more than two adults, while about 17% of the households have more than two children (less than 15 years old). To incorporate seasonal variation, we use *winter* (May-July) and *summer* (November-February) in our analysis. With respect to household appliances, we consider the ownership of *fridge* (refrigerator, or combined fridge freezer, or freestanding deep freezer) and energy choice for *modern cooking* (main energy source for cooking is electricity from grid, other source of electricity, gas, or solar energy). Moreover, it is assumed that ownership of basic equipment for social communication (cellphone) and self-entertainment (TV, radio or satellite TV) helps households achieve a reasonable standard of living.

Table 3 also shows that more than 88% of households own cellphones and self-entertainment in South Africa, while the ownership of a refrigerator or freezer for cold storage is less prevalent (80%); 83% of South African households use modern energy sources for daily cooking activities. In terms of settlement type, most of the households reside either in a urban formal (50%) or traditional areas (40%) in South Africa. We further include geysers in the semiparametric model, because water heating (often by electric geysers), rather than space heating is the largest end-use of electricity in the residential sector (Meyer, 2000). In addition, more than 50% of South African households stay in a medium to larger size home (no less than 60 m^2), not including renters. Within the survey data, the living space information for all but a few renters is recorded as "not applicable". This appears to be a mistake by the surveyors, as the questionnaire suggests that an estimate should be made; however, "not applicable" indicates a house-

[10]For a house with three adults and two children, but the same characteristics as the reference household, both the "Adults=3" and "Kids=2" binary variables will be set to 1, while all others will be turned off.

hold either not living in a permanent structure or in one with multiple households in one permanent structure (Stats SA, 2017b), which is consistent with a typical apartment complex. About 13% of the households are renters. In order to evaluate if receipt of FBE affects household energy requirements and expenditure behaviour, we generate the *FBE* indicator; about 14% of households report positive values for the FBE they received.

5. Results and discussion

5.1. Semiparametric model

To present the FGT results, we must estimate the household adjustment factors and determine the energy poverty line. The adjustment factors are based on the parameter estimates arising from the semiparametric model – see Table B.2. The energy equivalence scale for each household arises from Equation (4), while the energy poverty line is calculated from Equation (2). However, the poverty line is underpinned by the reference household, which is summarised in Table 4, and our reason for choosing the 75^{th} percentile of energy expenditure for the reference group as the reference energy requirement was discussed in the Methods section. The resulting reference energy expenditure is ZAR 231; below, we examine the sensitivity of our results to this percentile choice.

In addition to the reference group, we also summarise the estimated equivalence scales and poverty line values for all the households in Panel B. Our estimated energy equivalence scales range from 0.41 to 2.27, while the derived energy poverty line (i.e. household required energy consumption) falls between ZAR 94 and ZAR 524 per household per month. The mean poverty line, ZAR 242, is lower than the mean of actual monthly energy expenditure ZAR 300 with the total sample (Table 2).

5.2. Results of the FGT measures

Using the estimated household-specific energy poverty lines, we apply FGT to investigate the incidence, gap and severity of energy poverty in South Africa. Table 5 presents these estimates of energy poverty, as well as its decomposition across expenditure groups.

Table 3: Summary statistics of major variables ($N = 17166$).

Variable description	Mean	Standard deviation
Monthly total household expenditure (unit: ZAR)	7465.10	11637.47
Monthly energy expenditure (unit: ZAR)	300.29	351.11
Energy share (= energy expenditure/total expenditure)	0.07	0.06
Number of adults = 1	0.22	0.41
Number of adults = 2	0.32	0.47
Number of adults = 3	0.22	0.41
Number of adults = 4	0.14	0.34
Number of adults = 5	0.07	0.25
Number of adults = 6	0.03	0.17
Number of adults = 7	0.01	0.11
Number of children (age less than 15-year old) = 0	0.42	0.49
Number of children = 1	0.22	0.42
Number of children = 2	0.19	0.39
Number of children = 3	0.10	0.30
Number of children = 4	0.05	0.21
Number of children = 5	0.02	0.14
Urban formal: settlement type is urban formal	0.50	0.50
Urban informal: settlement type is urban informal	0.07	0.25
Traditional area: settlement type is traditional area[a]	0.40	0.49
Rural: settlement type is rural formal	0.03	0.17
Modern cooking: main energy source for cooking is electricity from grid, other source of electricity (e.g. generator etc.), gas, or solar energy	0.83	0.38
Fridge: household owns a refrigerator/combined fridge freezer, or freestanding deep freezer	0.80	0.40
Cellphone: household owns a cellphone	0.92	0.27
Entertainment: household owns a TV, a radio or a satellite TV (e.g. DStv/TopTV)	0.88	0.32
Geyser: household owns a electric water heater (geyser)	0.19	0.39
Summer: survey month in November, December, January or February	0.36	0.48
Winter: survey month in May, June or July	0.25	0.43
Estimated area of the dwelling unit:		
Very small space: less than 30 m^2	0.10	0.30
Small space: between 30 and 59 m^2	0.25	0.44
Medium space: between 60 and 119 m^2	0.34	0.48
Large space: between 120 and 239 m^2	0.14	0.35
Very large space: 240 m^2 or more	0.04	0.19
Renter: ownership of household's main dwelling is rented	0.13	0.33
FBE: the reported value of free basic electricity is postive	0.14	0.35

[a]: A traditional area refers to communally owned land under the jurisdiction of a traditional leader (Stats SA, 2017b).

Table 4: Descriptive statistics of reference group and semiparametric results.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Panel A: Reference group ($N = 44$)						
Monthly total household expenditure (unit: ZAR)	709.09	1543.51	2109.58	3517.62	4312.04	16192.75
Monthly energy expenditure (unit: ZAR)	89.92	99.74	179.84	196.58	231.10	802.40
Energy budget share	0.01	0.05	0.07	0.08	0.11	0.25
Panel B: Energy equivalence scale and energy poverty line ($N = 17166$)						
Energy equivalence scale	0.41	0.80	0.96	1.05	1.16	2.27
Energy poverty line (unit: ZAR/month)	94.41	185.84	222.74	242.21	268.88	524.49

Energy equivalence scale is calculated following Equation (4); energy poverty line (z_i) is calculated from Equation (2).

As shown in the table, in total, more than half (58%) of the households are energy poor, according to the headcount index (P_0), while the energy poverty gap (0.23) and severity (0.11) indexes are lower.

The expenditure group decomposition shows us that average energy poverty rates do not increase with total expenditure, and that is true for all three indexes. The headcount ratio ranges from a high of 88% amongst low-expenditure households down to 16% for high-expenditure households. And, given the 58% overall headcount, we can conclude that energy poverty is an extensive problem amongst South African households. Decomposing the gap allows us to put this into starker contrast. There is disparity from low- to high-expenditure, as would be expected; however, the energy expenditure shortfall is approximately 38% at the bottom, but only 5% at the top. When inequality and poverty are combined, as is done via the energy poverty severity index, we find that energy poverty is much more severe in the bottom expenditure groups than upper groups.

The decomposability property of FGT measures allows for the calculation of the proportion of total energy poverty shown in the last column of Table 5. As might be expected, the percentage contribution that lower expenditure subgroups make to the total energy severity is more than that of higher expenditure groups. For policy purposes, these differing contributions help focus policy discussions. Thus, we see that further energy support to lower-expenditure groups is warranted. We investigate some options along those lines, below.

Table 5: Energy poverty estimates by expenditure group.

Expenditure decile	Headcount index (P_0^k)	Energy poverty gap (P_1^k)	Energy poverty severity (P_2^k)	Percentage contribution to total P_2
1(lower)	0.88	0.38	0.20	17.31
2	0.80	0.33	0.16	14.13
3	0.75	0.30	0.15	13.05
4	0.72	0.29	0.15	12.71
5	0.66	0.26	0.13	11.15
6	0.59	0.23	0.11	9.78
7	0.53	0.20	0.10	8.48
8	0.43	0.16	0.08	7.03
9	0.32	0.11	0.05	4.25
10(upper)	0.16	0.05	0.02	2.09
Total	0.58	0.23	0.11	100.00

P_0^k denotes headcount rate of subgroup k; P_1^k denotes energy poverty gap of subgroup k; P_2^k denotes energy poverty severity of subgroup k. The percentage contribution of subgroup k to total is calculated as: $100(N_k/N)(P_\alpha^k/P_\alpha)$, where $\alpha = 0, 1$ or 2; N_k/N is population share of subgroup k. $N = 17166$.

When comparing our results to previous local studies, it is found that our estimates of the energy poverty incidence, the easiest to compare across studies, suggest more energy poverty than has been estimated by many, although most of them applied much older data than ours. For example, government estimates place energy poverty at 47% in 2012 and 43% in 2013 (DOE, 2012, 2013), while the 2012 energy poverty rate is 25% according to Ismail and Khembo (2015) or a lower 13 - 19% (Mbewe, 2018). The key difference between our estimation and the ones in the literature is that our estimates of energy poverty arises from the use of estimated required energy consumption instead of actual expenditure. For this reason, we compare our results with previous estimates that are based on alternative methods in Table 6. The Department of Energy (DOE, 2012, 2013) has used a 10% threshold as the poverty line, such that a household is defined to be energy poor if its energy share is greater than 10%. Hence, that poverty line, like ours,

Table 6: A comparison of FGT results with alternative poverty lines.

	Poverty line[a]: 10% of total household expenditure			Poverty line[b]: average energy expenditure of income poor		
Expenditure decile	P_0	P_1	P_2	P_0	P_1	P_2
1(lower)	0.64	0.45	0.69	0.87	0.39	0.20
2	0.31	0.17	0.21	0.76	0.30	0.14
3	0.23	0.12	0.15	0.66	0.26	0.12
4	0.18	0.09	0.09	0.61	0.24	0.11
5	0.14	0.07	0.08	0.52	0.19	0.08
6	0.12	0.05	0.06	0.43	0.16	0.07
7	0.08	0.03	0.02	0.32	0.12	0.05
8	0.06	0.04	0.05	0.20	0.08	0.04
9	0.04	0.02	0.02	0.10	0.04	0.02
10(upper)	0.01	0.00	0.00	0.04	0.01	0.01
Total	0.18	0.10	0.14	0.45	0.18	0.08

[a]: The poverty line is household-specific and calculated as monthly total household expenditure multiplied by 10%, hence a household is defined as energy poor if its monthly actual energy expenditure is greater than its own poverty line. [b]: Following Foster et al. (2000), the average energy expenditure for income poor group is ZAR 174 per household per month in our data, hence a household is recognised as energy poor if its actual monthly energy expenditure is less than ZAR 174. $N = 17166$.

is household-specific. In addition, we calculate another energy poverty line as average energy expenditure for income poor households, following Foster et al. (2000). In South Africa, income poor households are assumed to fall below the upper-bound poverty line (UBPL) from April 2015 (to match our data) - ZAR 992 per person per month (Stats SA, 2017c). Using this definition, we calculated average energy expenditure of ZAR 174 per household per month; this value is similar to the median of our reference household group.

The results in Table 6 show that energy poverty incidence, gap and severity rates are generally lower than those in Table 5, suggesting that (1) using actual energy expenditure for the 10% indicator probably underestimates energy poverty, (2) an energy poverty line defined within income poor households, only, might also underestimate energy poverty or (3) our reference level could be overestimated, which is why we offer the sensitivity analysis. One concern with using actual energy expenditure is that households may limit their energy expenditure, if they need to stretch their budget. That concern appears to be supported with this data and this comparison, given the lower poverty rates predicted from actual expenditure. Another concern that arises is that energy poverty and income poverty may not be separately identified. Identification is likely to be an even bigger worry, when the energy poverty line is determined by income-poor households; however, the method we apply does control for the income association with energy expenditure, and, therefore, implicitly separates income and energy poverty. Our results suggest that income poverty and energy poverty are correlated: poorer households are much more likely to be energy poor. However, our results do not suggest that all income/expenditure poor households are energy poor. We also do not find that energy poverty is exclusive to poor households.

Further, we see that income groups with greater energy poverty incidence have a larger energy poverty gap and greater severity; thus, energy poor households have very low levels of energy expenditure. The FGT measures, especially for the gap and severity, provide more information about energy poverty, due to the continuous nature of the data that is incorporated. Although the headcount index underscores the incidence of energy poverty, as other indicators do, it is insensitive to the degree of energy poverty and it is insensitive to the distribution of energy expenditure among the energy poor. For this reason, the energy poverty gap and severity indexes are complements to the headcount index.

5.3. Sensitivity analysis

For the initial analysis, we choose the 75^{th} percentile of energy expenditure for the reference group, and, therefore, energy poverty rates are determined by that assumption. In order to get some idea regarding the effect of this assumption, we consider alternative assumptions, see Figure 2. That figure includes poverty estimates underscored by assuming different points within the reference group energy expenditure distribution; specifically, we consider the 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles, as well as the mean. If a poverty line is based on the 50^{th} percentile, it is ZAR 179.84, compared to ZAR 343.11 at the 90^{th} percentile. Anywhere above the 50^{th} percentile, energy poverty is found to

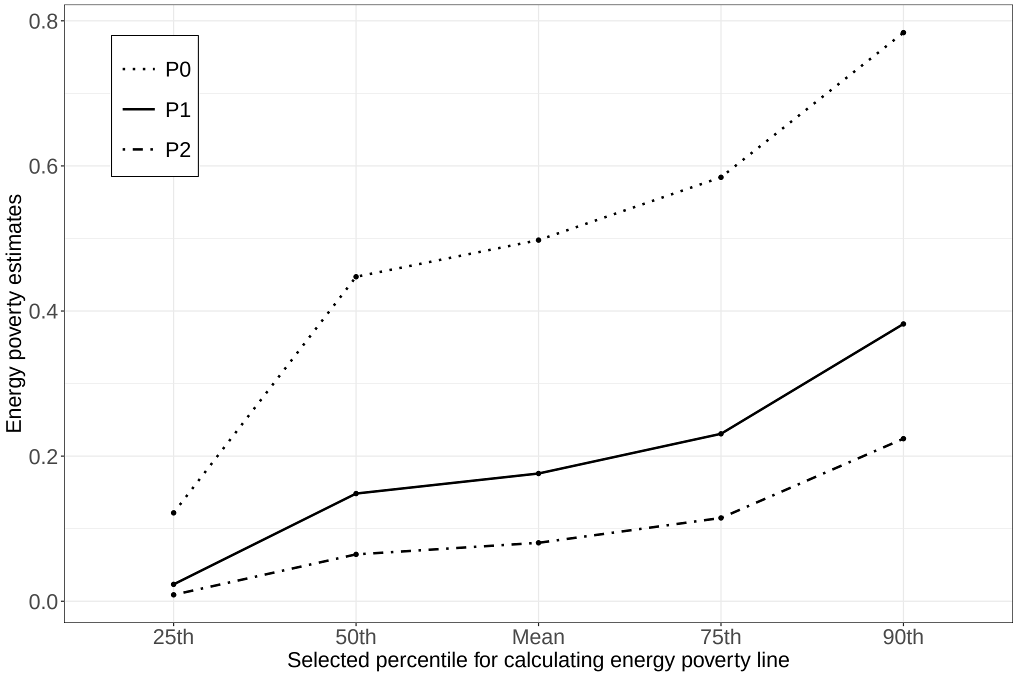

Figure 2: Sensitivity analysis. Note: The percentile in x axis refers to the distribution of energy expenditure of reference group; the value for each percentile is ZAR 99.74, ZAR 179.84, ZAR 196.58, ZAR 231.1, and ZAR 343.11, respectively.

be an extensive problem in South Africa, as it lies above 40%. And the energy poverty gap and severity also remain quite high.

6. A policy simulation

Given our understanding of who is energy poor and how poor they are, we can consider energy poverty mitigation policy that might target the most vulnerable energy poor households. For this policy scenario, we take the satisfaction of household energy requirements to be the policy priority, and ask whether or not the existing FBE policy is making a difference. Currently, FBE policy provides 50 kWh or more free electricity per month to indigent households, as long as they are connected to the grid; notably, municipalities differ in terms of implementation (Ye et al., 2018).[11]

[11] As mentioned in Section 2.2, some unelectrified households may be provided with free basic alternative energy (FBAE) if they are indigent-identified by the municipality. However, this information is

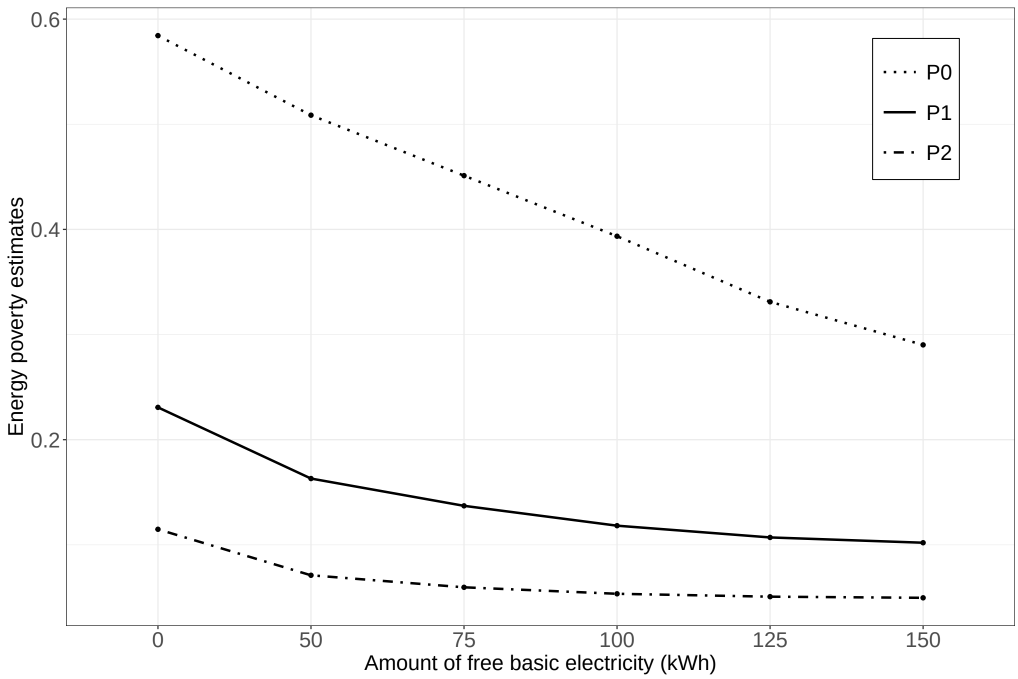

Figure 3: Percentage of energy poor households in each policy scenario ($N = 17166$).

Despite some of the data limitations, it is reasonably clear that the provision of FBE to indigent households (and possibly additional households) could lessen energy poverty. To analyse the impact of FBE policy on energy poverty in South Africa, we simulate a few scenarios – offering low-income households access to 50 kWh, 75 kWh, 100 kWh, 125 kWh, and 150 kWh FBE per month – to see how that impacts the energy poverty picture. We are not in a position to evaluate either the fiscal plausibility of these scenarios nor are we in a position to evaluate whether or not that amount of electricity could even be supplied by Eskom or the local municipality. Because our analysis has been underpinned by expenditure, rather than kWh, we assume a residential electricity price of 0.9806 ZAR/kWh, which was the annual average Eskom residential electricity price in 2014/2015 (DOE, 2018)), to turn each kWh of FBE into an energy expenditure equivalent.

not available in the LCS survey; thus, we only simulate the FBE policy.

For the simulation, we attempt to capture the indigent household concept that is the foundation of FBE. However, there are a range of definitions available. We could use a household income threshold for low-income households (Israel-Akinbo et al., 2018), or try to more carefully adapt what is done in some South African municipalities, which target the indigent households by setting an income threshold per household per month (DPLG, 2009). In this analysis, we use the South African upper-bound poverty line (UBPL) from April 2015. Thus, households with per capita expenditure below this threshold are defined to be income-poor, and, therefore, most likely to be indigent. As indicated by Stats SA (2015), individuals at the UBPL are assumed to be able to meet basic food and non-food needs; hence, individuals at/above the UBPL do not have to sacrifice food to obtain essential energy services for daily use. Furthermore, the UBPL in 2015 has been derived from the LCS 2014/2015 data; hence, it makes sense to use it here, as we are using the same dataset. According to Stats SA (2017c), the UBPL is ZAR 992 per person per month (about 2.76 USD per person per day) for April 2015. Given this value, 7837 households out of 17166 (45.6%) are defined as low-income households, among which 1252 households have reported a positive market value of FBE. In other words, these 1252 low-income households have already received at least some free electricity. Hence, they will only be assigned additional free electricity, if their reported FBE value is less than the one in the policy scenario, while the difference between these two values is the amount that will be given to the specific low-income household. For example, for the FBE = 50 kWh policy scenario, the market value of 50 kWh FBE is assumed to be ZAR 49.03 (= 50 kWh $\times$ 0.9806 ZAR/kWh), hence, a household who reported ZAR 40 for FBE will be assigned additional ZAR 9.03 (= $49.03 - 40$) to its monthly energy expenditure. And this new monthly energy expenditure will be substituted into Equation (1) to replace the actual energy expenditure, and finally to determine the incidence, gap and severity of energy poverty. For those low-income households that did not report receipt of FBE, they will be assigned exactly the amount of FBE for each policy scenario.

Although we expect that the receipt of FBE will reduce actual expenditure on energy, it is also expected to increase use; therefore, it is also important to note that we abstract from that possibility. Figure 3 presents the main findings from our energy poverty simulations. As expected, providing free electricity reduces the rates of energy poverty. For instance, if poor households receive 150 kWh per month the headcount ratio is estimated to fall from 58% to 29%. More importantly, there is a significant fall in the energy poverty severity index between the 'with FBE' and 'without FBE' scenarios, suggesting a positive FBE impact on the most energy deprived households.

7. Conclusion and policy implications

Although energy poverty is an international concern – this can be seen in the tenets of Sustainable Development Goal (SDG) 7, which seeks to "ensure access to affordable, reliable, sustainable and modern energy for all" (United Nations, 2021), – a full understanding of energy poverty requires a number of different approaches. Much of the literature that is available from developing countries has focused on binary indicators of household access to electricity, which, although easy to understand, are unlikely to capture the extent of energy poverty. Multidimensional measures of energy poverty offer additional context, because, as the name suggests, they capture multiple dimensions. Oftentimes, such studies include a measure of affordability, as well. However, such measures are sensitive to the weights applied, as well as the number of dimensions that are available, and, therefore are likely to benefit from a comparison with other approaches.

In this research, we offer corroborating evidence, as well as additional evidence, regarding the depth of energy poverty in one developing country, South Africa, using the most recent Living Conditions Survey. The FGT approach provides information on the incidence of energy poverty (which is also available from previous research that primarily focused on access to modern energy services), the energy poverty gap and the severity of energy poverty. This approach requires the specification of an energy poverty line. Such a line must be determined for the circumstances under consideration and often depends upon extensive data and/or engineering models. Instead, we use widely available data to estimate a poverty line using information on the share of energy expenditure, total household expenditure, household size and composition and other household dwelling characteristics, such as dwelling size, time of the year the data was collected and household appliances.

Our results suggest that energy poverty is extensive in the country, especially for lower income households. As expected, estimating energy poverty with household required energy consumption yields relatively higher estimates than those with actual energy expenditure in local literature; thus, applying equivalence scale methods to determine an energy poverty line is reasonable. As is well known, FGT measures incorporate binary indicators, as well as continuous measures. Therefore, we are able to offer a more nuanced picture of energy poverty than is available with just binary indicators or multidimensional measures.

Our research offers many potential policy insights. First, compared with previous binary or multidimensional measures, this study offers a different view for policy-makers; it even offers an estimate of a household specific poverty line that could be adjusted for a wider set of policy goals. Second, our research illustrates distinct income poor and energy poor households. Because interventions for alleviating income poverty and energy poverty normally differ, policy makers can use an approach like the above to separately focus on household energy requirement determinants, rather than household income. Third, the severity of energy poverty suggests that relevant energy poverty alleviation policies should pay more attention to the most energy deprived households, in order to eliminate extreme poverty. Fourth and finally, since the affordability and reliability of energy services are important indicators in energy poverty measurement, it is possible to incorporate our household required energy (affordability concept) into a multidimensional measure in order to examine other deprivations of energy services/consumption.

Acknowledgements

We are grateful to three anonymous reviewers and the handling editor for the constructive suggestions. We would like to thank *Economic Research Southern Africa* (ERSA) for its support of this research. We also thank the participants in the *1st South African Association for Energy Economics (SAAEE) Conference*, and three external examiners of Yuxiang's PhD thesis for the valuable comments and conversations on an earlier version of this paper.

CRediT authorship contribution statement

YY: Conceptualisation, Methodology, Data analysis, Writing - original draft, review & editing. SK: Conceptualisation, Methodology, Data analysis, Supervision, Writing - review & editing.

Declarations of interest

None.

Appendix A. Summary statistics of retained and dropped samples

Table A.1: Summary statistics of retained and dropped samples.

	Retained sample ($N = 17166$)		Dropped sample ($N = 6214$)		
	Mean	Standard deviation	Sample size	Mean	Standard deviation
Monthly total household expenditure (unit: ZAR)	7465.10	11637.47	6214	7308.20	10943.83
Monthly energy expenditure (unit: ZAR)	300.29	351.11	6214	222.03	304.79
Energy share	0.07	0.06	6214	0.05	0.07
Number of adults = 1	0.22	0.41	6214	0.34	0.47
Number of adults = 2	0.32	0.47	6214	0.33	0.47
Number of adults = 3	0.22	0.41	6214	0.14	0.35
Number of adults = 4	0.14	0.34	6214	0.08	0.27
Number of adults = 5	0.07	0.25	6214	0.04	0.20
Number of adults = 6	0.03	0.17	6214	0.02	0.14
Number of adults = 7	0.01	0.11	6214	0.01	0.10
Number of children = 0	0.42	0.49	6214	0.53	0.50
Number of children = 1	0.22	0.42	6214	0.18	0.39
Number of children = 2	0.19	0.39	6214	0.13	0.34
Number of children = 3	0.10	0.30	6214	0.06	0.23
Number of children = 4	0.05	0.21	6214	0.03	0.17
Number of children = 5	0.02	0.14	6214	0.01	0.12
Urban formal	0.50	0.50	6214	0.64	0.48
Urban informal	0.07	0.25	6214	0.07	0.26
Traditional area	0.40	0.49	6214	0.23	0.42
Rural	0.03	0.17	6214	0.06	0.23
Modern cooking	0.83	0.38	6183	0.83	0.38
Fridge	0.80	0.40	5870	0.65	0.48
Cellphone	0.92	0.27	6121	0.91	0.29
Entertainment	0.88	0.32	5906	0.80	0.40
Geyser	0.19	0.39	6017	0.16	0.37
Summer	0.36	0.48	6214	0.36	0.48
Winter	0.25	0.43	6214	0.25	0.44
Very small space	0.10	0.30	5780	0.05	0.23
Small space	0.25	0.44	5780	0.10	0.29
Medium space	0.34	0.48	5780	0.14	0.35
Large space	0.14	0.35	5780	0.07	0.25
Very large space	0.04	0.19	5780	0.02	0.16
Renter	0.13	0.33	6158	0.56	0.50
FBE	0.14	0.35	6214	0.06	0.23

Note: This table shows the mean of selected variables for both the retained and dropped samples in the LCS 2014/2015 data. Within the dropped samples (6214), the number of observations for each variable could vary due to missing information related to that variable.

Appendix B. Semiparametric regression estimates

Table B.2: Semiparametric index model parameter estimates (N = 17166).

Variable	Scaling coefficient	Standard error
Log of total household expenditure[1]	1.0000^a	(0.000)
Number of adults = 2	-0.0094^a	(0.001)
Number of adults = 3	-0.1027^a	(0.001)
Number of adults = 4	-0.1384^a	(0.001)
Number of adults = 5	-0.1527^a	(0.001)
Number of adults = 6	-0.1114^a	(0.002)
Number of adults = 7	-0.0110^b	(0.004)
Number of children = 1	-0.0108^a	(0.001)
Number of children = 2	0.0034^a	(0.001)
Number of children = 3	0.0625^a	(0.001)
Number of children = 4	0.0586^a	(0.002)
Number of children = 5	0.0572^a	(0.002)
Urban informal	0.1310^a	(0.001)
Traditional area	0.2090^a	(0.001)
Rural	0.0061^a	(0.002)
No modern cooking	0.3204^a	(0.001)
No fridge	0.0996^a	(0.001)
No cellphone	-0.0360^a	(0.001)
No entertainment	0.0279^a	(0.001)
Geyser	-0.4172^a	(0.001)
Summer	-0.0101^a	(0.001)
Winter	-0.0489^a	(0.001)
Very small space	0.0335^a	(0.001)
Medium space	-0.0545^a	(0.001)
Large space	-0.0911^a	(0.001)
Very large space	-0.1790^a	(0.002)
Renter	-0.0371^a	(0.001)
FBE	0.1853^a	(0.002)

Parameter estimates from semiparametric least squares applied to Equation (3); see Ichimura (1993) for estimation details. Significance levels: ^{a} - 0.005, ^{b} - 0.01, ^{c} - 0.05, ^{d} - 0.1. Additional notes: [1] - For identification, this parameter estimate is set to unity.

References

Alkire, S., Foster, J., 2011. Counting and multidimensional poverty measurement. Journal of Public Economics 95, 476–487.

Balmer, M., 2007. Energy poverty and cooking energy requirements: the forgotten issue in South African energy policy? Journal of Energy in Southern Africa 18, 4–9.

Barnes, D.F., Khandker, S.R., Samad, H.A., 2011. Energy poverty in rural Bangladesh. Energy Policy 39, 894–904.

Bednar, D.J., Reames, T.G., 2020. Recognition of and response to energy poverty in the United States. Nature Energy 5, 432–439.

Bhatia, M., Angelou, N., 2015. Beyond connections: energy access redefined. World Bank.

Blackorby, C., Donaldson, D., 1993. Adult-equivalence scales and the economic implementation of interpersonal comparisons of well-being. Social Choice and Welfare 10, 335–361.

Blundell, R., Lewbel, A., 1991. The information content of equivalence scales. Journal of Econometrics 50, 49–68.

Boardman, B., 1991. Fuel poverty: from cold homes to affordable warmth. London, UK: Belhaven Press.

Bohlmann, J., Inglesi-Lotz, R., 2020. Examining the determinants of electricity demand by South African households per income level. Energy Policy 148, 111901.

Bohlmann, J.A., Inglesi-Lotz, R., 2018. Analysing the South African residential sector's energy profile. Renewable and Sustainable Energy Reviews 96, 240–252.

Bradshaw, J., Middleton, S., Davis, A., Oldfield, N., Smith, N., Cusworth, L., Williams, J., 2008. A minimum income standard for Britain: what people think. Joseph Rowntree Foundation, York, UK.

Bravo, V., Mendoza, G.G., Legisa, J., Suárez, C.E., Zyngierman, I., 1983. A first approach to defining basic energy needs. United Nations University, Japan, HSDRGPID-71/UNUP-454.

Charlier, D., Legendre, B., 2019. A multidimensional approach to measuring fuel poverty. The Energy Journal 40, 27–53.

Charlier, D., Legendre, B., Risch, A., 2019. Fuel poverty in residential housing: providing financial support versus combatting substandard housing. Applied Economics 51, 5369–5387.

Chidebell-Emordi, C., 2015. The African electricity deficit: computing the minimum energy poverty line using field research in urban Nigeria. Energy Research & Social Science 5, 9–19.

Churchill, S.A., Smyth, R., 2020. Ethnic diversity, energy poverty and the mediating role of trust: evidence from household panel data for Australia. Energy Economics 86, 104663.

Churchill, S.A., Smyth, R., Farrell, L., 2020. Fuel poverty and subjective wellbeing. Energy Economics 86, 104650.

Davis, S., Hughes, A., Louw, K., 2008. The impact of free basic electricity on the energy choices of low income households: a case study in South Africa. Program on Energy and Sustainable Development (PESD), PESD Working Paper 80. Stanford University, USA.

Deaton, A., Grosh, M., 2000. Consumption, in: Grosh, M., Glewwe, P. (Eds.), Designing household survey questionnaires for developing countries. World Bank, Washington, DC, pp. 91–134.

Deller, D., 2018. Energy affordability in the EU: the risks of metric driven policies. Energy policy 119, 168–182.

DME, 2003. Guidelines for the introduction of free basic electricity services. Department of Minerals and Energy (DME), Pretoria, South Africa.

DME, 2007. Free basic alternative energy policy: households energy support programme. Department of Minerals and Energy (DME), Pretoria, South Africa.

DOE, 2012. A survey of energy-related behaviour and perceptions in South Africa. Department of Energy (DOE): the residential sector, Pretoria, South Africa.

DOE, 2013. A survey of energy-related behaviour and perceptions in South Africa. Department of Energy (DOE): the Residential Sector, Pretoria, South Africa.

DOE, 2018. South African Energy Price Report 2018. Department of Energy (DOE), Pretoria, South Africa.

DOE, 2019. The South African Energy Sector Report 2019. Department of Energy (DOE), Pretoria, South Africa. ISBN: 978-1-920435-17-2.

Dong, Y., 2010. Endogenous regressor binary choice models without instruments, with an application to migration. Economics Letters 107, 33–35.

DPLG, 2009. Guidelines for the implementation of the National Indigent Policy by municipalities. Department of Provincial and Local Government (DPLG). Pretoria, South Africa.

Eskom, 2015. Integrated Report 2015. Eskom, Johannesburg, South Africa.

Essex, S., de Groot, J., 2019. Understanding energy transitions: the changing versions of the modern infrastructure ideal and the 'energy underclass' in South Africa, 1860–2019. Energy Policy 133, 110937.

Foster, J., Greer, J., Thorbecke, E., 1984. A class of decomposable poverty measures. Econometrica 52, 761–766.

Foster, J., Greer, J., Thorbecke, E., 2010. The Foster–Greer–Thorbecke (FGT) poverty measures: 25 years later. Journal of Economic Inequality 8, 491–524.

Foster, V., Tre, J.P., Wodon, Q., 2000. Energy prices, energy efficiency, and fuel poverty. Latin America and Caribbean Regional Studies Programme. Washington, DC: World Bank.

Greer, J., Thorbecke, E., 1986. A methodology for measuring food poverty applied to Kenya. Journal of Development Economics 24, 59–74.

Guild, J., Shackleton, C., 2018. Informal urban fuelwood markets in South Africa in the context of socio-economic change. Energy Policy 117, 136–141.

Haughton, J., Khandker, S.R., 2009. Handbook on poverty and inequality. World Bank. Washington, DC.

Hayfield, T., Racine, J.S., 2008. Nonparametric econometrics: the np package. Journal of Statistical Software 27, 1–32.

Heindl, P., 2015. Measuring fuel poverty: general considerations and application to German household data. FinanzArchiv: Public Finance Analysis 71, 178–215.

Heindl, P., Schüssler, R., 2015. Dynamic properties of energy affordability measures. Energy Policy 86, 123–132.

Hernández, D., 2016. Understanding 'energy insecurity' and why it matters to health. Social Science & Medicine 167, 1–10.

Herrero, S.T., 2017. Energy poverty indicators: a critical review of methods. Indoor and Built Environment 26, 1018–1031.

Hills, J., 2011. Fuel poverty: the problem and its measurement. Department of Energy and Climate Change (DECC), London, UK.

Hills, J., 2012. Getting the measure of fuel poverty: final report of the fuel poverty review. Department of Energy and Climate Change (DECC), London, UK.

Ichimura, H., 1993. Semiparametric least squares (SLS) and weighted SLS estimation of single-index models. Journal of Econometrics 58, 71–120.

IEA, 2009. World Energy Outlook 2009. International Energy Agency (IEA). IEA: Paris, France.

IEA, IRENA, UNSD, World Bank, WHO, 2021. Tracking SDG 7: The Energy Progress Report 2021. World Bank. Washington DC.

Ismail, Z., Khembo, P., 2015. Determinants of energy poverty in South Africa. Journal of Energy in Southern Africa 26, 66–78.

Israel-Akinbo, S., Snowball, J., Fraser, G., 2018. An investigation of multidimensional energy poverty amongst South African low-income households. South African Journal of Economics 86, 468–487.

Jiang, L., Yu, L., Xue, B., Chen, X., Mi, Z., 2020. Who is energy poor? Evidence from the least developed regions in China. Energy Policy 137, 111–122.

Khandker, S.R., Barnes, D.F., Samad, H.A., 2012. Are the energy poor also income poor? Evidence from India. Energy policy 47, 1–12.

Krugmann, H., Goldemberg, J., 1983. The energy cost of satisfying basic human needs. Technological forecasting and social change 24, 45–60.

Kyprianou, I., Serghides, D., Varo, A., Gouveia, J., Kopeva, D., Murauskaite, L., 2019. Energy poverty policies and measures in 5 EU countries: a comparative study. Energy and Buildings 196, 46–60.

Lazear, E.P., Michael, R.T., 1980. Family size and the distribution of real per capita income. American Economic Review 70, 91–107.

Legendre, B., Ricci, O., 2015. Measuring fuel poverty in France: which households are the most fuel vulnerable? Energy Economics 49, 620–628.

Leibbrandt, M., Finn, A., Oosthuizen, M., 2016. Poverty, inequality, and prices in post-apartheid South Africa, in: Arndt, C., McKay, A., Tarp, F. (Eds.), Growth and Poverty in Sub-Saharan Africa. Oxford University Press, Oxford, UK, pp. 393–417.

Li, K., Lloyd, B., Liang, X.J., Wei, Y.M., 2014. Energy poor or fuel poor: what are the differences?

Energy Policy 68, 476–481.

Liddell, C., Morris, C., McKenzie, S., Rae, G., 2012. Measuring and monitoring fuel poverty in the UK: national and regional perspectives. Energy Policy 49, 27–32.

Madubansi, M., Shackleton, C.M., 2006. Changing energy profiles and consumption patterns following electrification in five rural villages, South Africa. Energy Policy 34, 4081–4092.

Masekameni, D.M., Kasangana, K.K., Makonese, T., Mbonane, T.P., 2018. Dissemination of free basic electricity in low-income settlements. 3-5 April 2018, 2018 International Conference on the Domestic Use of Energy (DUE), IEEE. Cape Town, South Africa.

Mbewe, S., 2018. Investigating household energy poverty in South Africa by using unidimensional and multidimensional measures, CSAE Conference 2018: Economic Development in Africa, CSAE2018-206; Centre for the Study of African Economies (CSAE), Oxford, UK.

Memmott, T., Carley, S., Graff, M., Konisky, D.M., 2021. Sociodemographic disparities in energy insecurity among low-income households before and during the COVID-19 pandemic. Nature Energy , 1–8.

Mendoza Jr, C.B., Cayonte, D.D.D., Leabres, M.S., Manaligod, L.R.A., 2019. Understanding multidimensional energy poverty in the Philippines. Energy Policy 133, 110886.

Meyer, J.P., 2000. A review of domestic hot-water consumption in South Africa. R & D Journal 16, 55–61.

Mohr, T.M., 2018. Fuel poverty in the US: evidence using the 2009 Residential Energy Consumption Survey. Energy Economics 74, 360–369.

Moore, R., 2012. Definitions of fuel poverty: implications for policy. Energy Policy 49, 19–26.

Mvondo, J.M., 2010. Impact of access to free basic electricity on households' poverty in Buffalo city municipality in the Eastern Cape. Master thesis. University of Fort Hare.

Nelson, J.A., 1988. Household economies of scale in consumption: theory and evidence. Econometrica 56, 1301–1314.

Ningi, T., Taruvinga, A., Zhou, L., 2020. Determinants of energy security for rural households: the case of Melani and Hamburg communities, Eastern Cape, South Africa. African Security Review 29, 299–315.

Nussbaumer, P., Bazilian, M., Modi, V., 2012. Measuring energy poverty: focusing on what matters. Renewable and Sustainable Energy Reviews 16, 231–243.

Okushima, S., 2017. Gauging energy poverty: a multidimensional approach. Energy 137, 1159–1166.

Pachauri, S., Mueller, A., Kemmler, A., Spreng, D., 2004. On measuring energy poverty in Indian households. World development 32, 2083–2104.

Pachauri, S., Rao, N.D., 2020. Advancing energy poverty measurement for SDG7. Progress in Energy 2, 043001.

Pachauri, S., Spreng, D., 2004. Energy use and energy access in relation to poverty. Economic and Political weekly 39, 271–278.

Papada, L., Kaliampakos, D., 2020. Being forced to skimp on energy needs: a new look at energy poverty in Greece. Energy Research & Social Science 64, 101450.

Parikh, J.K., 1978. Energy use for subsistence and prospects for development. Energy 3, 631–637.

Pendakur, K., 1999. Semiparametric estimates and tests of base-independent equivalence scales. Journal of Econometrics 88, 1–40.

Pereira, M.G., Freitas, M.A.V., da Silva, N.F., 2011. The challenge of energy poverty: Brazilian case study. Energy Policy 39, 167–175.

R Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. URL: `https://www.R-project.org/`.

Robinson, C., 2019. Energy poverty and gender in England: a spatial perspective. Geoforum 104, 222–233.

Romero, J.C., Linares, P., López, X., 2018. The policy implications of energy poverty indicators. Energy Policy 115, 98–108.

Sen, A., 1976. Poverty: an ordinal approach to measurement. Econometrica 44, 219–231.

Simshauser, P., 2021. Vulnerable households and fuel poverty: measuring the efficiency of policy targeting in Queensland. Energy Economics , 105405.

Stats SA, 2015. Rebasing national poverty lines and development of pilot provincial poverty lines for South Africa. Statistics South Africa (Stats SA). Pretoria, South Africa.

Stats SA, 2017a. Living Conditions Survey 2014-2015 [dataset]. Version 1.1. Statistics South Africa (Stats SA). Pretoria: Statistics South Africa (Stats SA) [producer]. Cape Town: DataFirst [distributor], 2017.

Stats SA, 2017b. Living Conditions Survey 2014/2015 metadata. Statistics South Africa (Stats SA). Pretoria, South Africa.

Stats SA, 2017c. Poverty trends in South Africa: an examination of absolute poverty between 2006 and 2015. Statistics South Africa (Stats SA), Pretoria, South Africa.

Stats SA, 2019. Statistical release P0318: General Household Survey 2018. Statistics South Africa (Stats SA). Pretoria, South Africa.

Stats SA, 2020. Statistical release P0318: General Household Survey 2019. Statistics South Africa (Stats SA). Pretoria, South Africa.

Stats SA, 2021a. CPI History. Statistics South Africa (Stats SA), Pretoria, South Africa. URL: `https://www.statssa.gov.za/publications/P0141/CPIHistory.pdf[Accesseddate:2021-07-03]`.

Stats SA, 2021b. Non-financial census of municipalities for the year ended 30 June 2019. Statistics South Africa (Stats SA). Pretoria, South Africa.

Tait, L., 2017. Towards a multidimensional framework for measuring household energy access: application to South Africa. Energy for Sustainable Development 38, 1–9.

Thomson, H., Snell, C.J., Liddell, C., 2016. Fuel poverty in the European Union: a concept in need of definition? People, Place & Policy Online , 5–24.

Uhunamure, S.E., Nethengwe, N.S., Musyoki, A., 2017. Driving forces for fuelwood use in households in the Thulamela municipality, South Africa. Journal of Energy in Southern Africa 28, 25–34.

United Nations, 2021. The Sustainable Development Goals Report 2021. New York: United Nations.

Vermaak, C., Kohler, M., Rhodes, B., 2014. Developing an energy-based poverty line for South Africa. Journal of Economic and Financial Sciences 7, 127–144.

Visagie, E., 2008. The supply of clean energy services to the urban and peri-urban poor in South Africa. Energy for Sustainable Development 12, 14–21.

Welsch, H., Biermann, P., 2017. Energy affordability and subjective well-being: evidence for European countries. The Energy Journal 38, 159–176.

Winkler, H., Simões, A.F., La Rovere, E.L., Alam, M., Rahman, A., Mwakasonda, S., 2011. Access and affordability of electricity in developing countries. World development 39, 1037–1050.

Yatchew, A., Sun, Y., Deri, C., 2003. Efficient estimation of semiparametric equivalence scales with evidence from South Africa. Journal of Business & Economic Statistics 21, 247–257.

Ye, Y., Koch, S.F., Zhang, J., 2018. Determinants of household electricity consumption in South Africa. Energy Economics 75, 120–133.

Ye, Y., Koch, S.F., Zhang, J., 2020. Modelling required energy consumption with equivalence scales. Economic Research Southern Africa Working Paper No 809.

Zhang, D., Li, J., Han, P., 2019. A multidimensional measure of energy poverty in China and its impacts on health: an empirical study based on the China family panel studies. Energy Policy 131, 72–81.