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

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ERSA working paper 843

December 2020

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December 10, 2020

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Abstract

Energy poverty is a major concern in most of developing countries while its measurement has not been fully addressed due to the complexity of energy basic needs estimation. This study contributes to the literature by measuring energy poverty with focus on household required energy consumption using widely available household budget survey data. We apply the Foster-Greer-Thorbecke (FGT) poverty measures in a developing but somewhat energy advanced context, South Africa. Our energy poverty line is based on household dependent required energy consumption, and we use data from a recent South African Living Conditions Survey. We find that headcount energy poverty is extensive, 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. Our results are consistent with those from previous research, which suggests that our measure of required energy may be a reasonable option for understanding energy poverty.

Keywords: Energy poverty, Required energy consumption, FGT poverty measures

1 Introduction

In 2016, about one billion people could not access electricity, while the electrification rate in sub-Saharan Africa was only 43% (IEA, 2017). Binary indicators of household access to electricity, such as access to electricity, are easy to understand and are often used, as above, to describe energy poverty, the situation wherein household basic energy need cannot be met (e.g., Boardman, 1991; Foster et al., 2000; Sovacool et al., 2012; Welsch and Biermann, 2017). However, binary indicators do not capture the full extent of energy poverty. For instance, some households have access, but are not able to afford electricity (Ye et al., 2018; Zhang et al., 2019), and, therefore, mixed energy use is quite common. As IEA (2017) reports, one-third of the world's population still rely on solid biomass for cooking, and most of those are living in developing Asia and sub-Saharan Africa. 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 (Nussbaumer et al., 2012). For instance, Tait (2017) develops a framework to measure energy access from four dimensions: fuel use, affordability, safety and reliability in South Africa, while Zhang et al. (2019) measure energy poverty in China by considering access to modern forms of energy for cooking and energy affordability. The multidimensional energy poverty index (MEPI) incorporates diverse dimensions related to residential energy consumption. However, there are limitations associated with multidimensional measures, due to the application of arbitrary weights for each factor; thus, the results can vary with the weight assigned to each factor.

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 potentially offer a description of energy affordability through the relationship between what the household *needs to spend on energy* and the household's total income or expenditure (Welsch and Biermann, 2017; Heindl and Schüssler, 2015; Deller, 2018). For instance, the 10% indicator (Boardman, 1991) defines energy affordability as an energy poverty ratio - the ratio between required household energy expenditure and household total income.

While much research in energy poverty measurement in developing countries has focused on access to modern energy services (Nussbaumer et al., 2012), less of it considers poverty with respect to household energy requirements. In application, though, 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). 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 this study, we overcome that stumbling block - see below - which allows us to apply Foster-Greer-Thorbecke (FGT) measures (Foster et al., 1984) to examine energy poverty in a developing, but somewhat energy advanced context, South Africa. The FGT measures provide information on the incidence of poverty (headcount index), while allow a further 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) It also 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 subsets of households is expected to be of interest to policymakers, because it can point to targeted interventions. We exploit that thinking in our analysis, as well, to see if an extension of the current free basic electricity program in the country has the potential to mitigate energy poverty and severity.

The FGT measures require an energy poverty line – household energy need is conceptually similar to an energy poverty line – but offer evidence related to the incidence and severity of poverty. Foster et al. (2000) apply FGT measures defining the energy poverty line to be average energy consumption for households whose overall per capita consumption level falls at or below the income poverty line of the country. Although their energy poverty line is easy to adapt and calculate from income and expenditure survey data, it is based on the assumption that energy poor households are also income poor (Khandker et al., 2012); therefore, it potentially conflates energy poverty and income poverty. Moreover, Heindl (2015) applies 10% energy share as poverty line to estimate energy poverty severity and incidence in Germany. It only considers households with income below median, and is not able to incorporate household energy requirement in the estimation.

Furthermore, a single fixed energy poverty line may not be appropriate. 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).

For that reason, we apply the semiparametric equivalence scale method proposed by Ye et al. (2020), which adjusts a baseline energy expenditure value to account for household differences in composition and electric appliance ownership to determine need.

Given this methodology, our FGT analysis is underscored by household dependent energy poverty lines, such that a household is defined to be energy poor if it does not purchase the energy it needs. Our estimates provide a wider picture of energy poverty in South Africa than is available from simple access measures, because we incorporate all aspects of domestic energy consumption. Furthermore, we weight those sources according to the market, because we are using observed purchase behaviour. We feel that weighting to the market is less arbitrary than the multidimensional weights that are often used.

We find that about half of the sampled South African households are energy poor according to the headcount index, while the energy poverty severity index is lower. We compare our results to previous research in the country for validation of our measure, and consider the sensitivity of our results to some of the assumptions. After decomposition across income groups, we find 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 Background

2.1 Energy consumption in South African households

Prior to 1990, less than a third of the South African population had access to electricity (Bekker et al., 2008), while a majority of households used numerous fuels, such as: firewood, kerosene, candle, coal and other traditional energy sources together with electricity for daily usage. Davis (1998) finds that in rural areas, both electrified and non-electrified households prefer to use two or more fuels for cooking. Furthermore, he finds differences between low-income and high-income households. Specifically, at low income levels electrified and non-electrified households use similar fuels, with electricity seen as an additional fuel; in high-income households electricity mainly displaces other fuels.

After the democratisation in 1994, the new South African government considered electricity provision for all to be essential for the economic growth and development of the country (DME, 2003a). Due to the national electrification programme they started (Essex and de Groot, 2019), the electrification rate reached 90% in 2018, up from 58% in 1996; for rural areas, the percentage of the population with access increased from 24% to 90% (Figure 1). 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, 2018c). By 2012, domestic energy consumption accounted for 25% of total electricity consumption (DOE, 2016), a proportion that has likely increased as the demand of energy-using assets increases with rising incomes in developing countries (Wolfram et al., 2012; Gertler et al., 2016).

Despite the increase in electrification rates and the availability of 6 kWh per month of free electricity, over 90% of households still used fuelwood for thermal purposes, especially cooking, (Madubansi and Shackleton, 2006, 2007). 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.

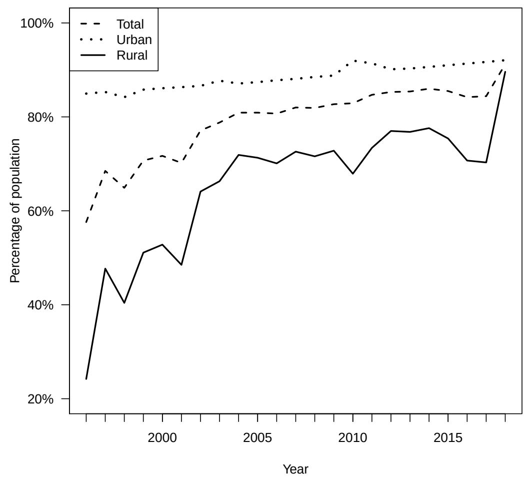

Figure 1: Percentage of population with access to electricity in South Africa, 1996-2018[2].

Visagie (2008) focuses on the household energy situation in the rapidly growing poor urban and peri-urban areas of South Africa, concluding that access to electricity is not the main problem for the majority of the urban and peri-urban poor; rather, the problem is the ability to afford the service. Affordability is not expected to have improved, primarily because of the rapid rise in electricity prices. From 2008 to 2018, Eskom's average domestic electricity price has more than doubled (DOE, 2018b), while the consumer price index (CPI) has increased by approximately 150% (Stats SA, 2018a). 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. Moreover, Bohlmann and Inglesi-Lotz (2020) conclude that elec-

[2]Source: The World Bank; see `https://data.worldbank.org/country/south-africa` [accessed at 2020-8-29].

tricity prices have 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 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 2, 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.

Unfortunately, South Africa's economy and development have been constrained by limited power generation capacity for a long time. Investments in generation capacity have failed to keep up with economic growth between 1994 and 2007, such that the excess supply created during the 1960s and 1970s was quickly absorbed (Bekker et al., 2008; Bohlmann et al., 2016). In the last decade, the country has experienced (and continues to experience) an electricity crisis. The first energy crisis, in 2008, forced consumers and businesses to learn to deal with rolling blackouts, which were used to forcibly reduce demand on the system. From near the end of 2014 to early 2015, the country was again severely affected, and by 2017, load-shedding had become a relatively common

[4] Source: Stats SA (2018c).

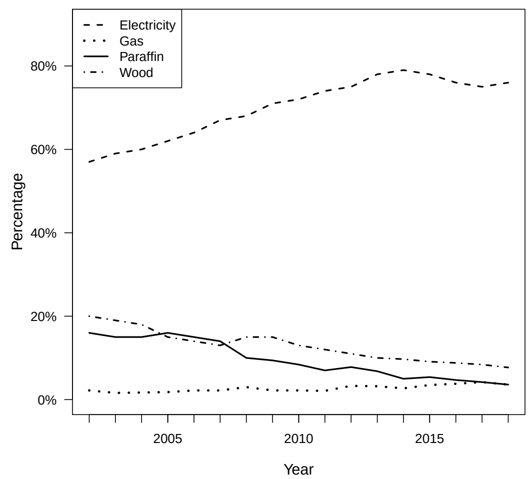

Figure 2: Percentage distribution of main energy sources used for cooking, 2002-2018[4].

occurrence, so common that an app has been developed to allow users to follow the schedule and plan their days around expected load shedding times.[5] The interrupted supply of electricity has had a negative effect on the economy (Goldberg, 2016) and energy end-users. Although similar studies are not available for South Africa, Umar and Kunda-Wamuwi (2019) find that load-shedding disrupts poor households' daily lives in urban residential areas in Zambia. In summary, power outages have resulted in inconvenience and cost to domestic consumers, it could aggravate the energy burden for low-income households and therefore affect their future energy requirements and choices.

[5]For example, "EskomSePush" has been widely used to follow load shedding schedules and receive push notifications about loadshedding expectations in South Africa. For more details about the app, please, refer to the website: `https://sepush.co.za/`.

2.2 Energy poverty in South African households

A number of recent papers consider the breadth and depth of energy poverty in South Africa. 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.

Although there is prevalent income poverty in South Africa (Leibbrandt et al., 2016), direct and indirect government projects have been implemented to eliminate energy poverty (Balmer, 2007), such as: free basic electricity (FBE) policy (DME, 2003b); support for energy efficient lighting (Ye et al., 2013, 2014); building code changes and energy efficient appliance labeling (DOE, 2018a); as well as demand side management programmes (Setlhaolo et al., 2014). The FBE policy provides free electricity to indigent households connected to the national grid in order to support them in meeting their basic energy needs. The initial FBE was 50 kWh per household per month, subject to registration

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%

[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).

in the indigent programme and installation of a prepaid meter.[6] In 2017, more

[6]This proposed level of basic electricity is motivated on the following basis: 56% of households in South Africa connected to the national grid (in Eskom's licensed areas) consume on average less than 50kWh of electricity per month. This is more than the lowest two quintiles of the population than can be classified as poor. 50kWh per month is considered

than 80% of the municipalities provided 50 kWh or more to indigent households; about 60% of municipality-identified indigent households have received the FBE (Stats SA, 2018b).

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 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. Furthermore, 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. Meanwhile, Mvondo (2010) 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.

adequate electrical energy to meet the needs for lighting, media access and limited water heating and basic ironing (or basic cooking) for a poor household (DME, 2003a). It was about ZAR 22 in 2003 (Eskom's HOMELIGHT domestic average tariff was 43.35 cents/kWh in 2003, 1 ZAR=100 cents, 50 kWh $\times$ 43.35 cents/kWh=21.67 ZAR).

3 Methods

3.1 Poverty measures

The FGT class of poverty measures proposed by Foster et al. (1984) has been widely applied in the assessment of incidence and depth of poverty (Foster et al., 2010). In general application, the FGT measures include the headcount ratio, poverty gap index and poverty severity index. The headcount index indicates the proportion of households that are below the poverty line. The poverty gap index measures the extent to which households fall below the poverty line, as a proportion of the poverty line. 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.

With respect to the poverty line, Greer and Thorbecke (1986) argue that a single poverty line applicable to all groups is not reasonable, because a poverty line should reflect local preferences and prices. For energy poverty, the energy poverty line should also account for factors relevant to household basic energy needs. Therefore, we apply household-specific energy poverty lines to the, otherwise, standard FGT measures:

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

where N is the total number of households, α is the sensitivity of the index to energy poverty, z_i is the household-specific energy poverty line and y_i is the household's actual energy expenditure i. $\mathbb{I}(\cdot)$ is an indicator function. For $\alpha = 0$, P_0 is the headcount index; for $\alpha = 1$, P_1 is the poverty gap index; for $\alpha = 2$, P_2, which puts higher weight on poorer households, is the energy poverty severity index.

Although a one-size-fits-all poverty line is common,[7] energy poverty levels should reflect real differences in need accounting for variations in the size and composition of the household. In other words, a fixed energy poverty line could ignore heterogeneity across households. We base the poverty line on household required energy consumption (REC), following the equivalence scale method proposed by Ye et al. (2020). Intuitively, the method estimates adjustment factors which are then used to rescale a baseline measure of required energy expenditure to determine the required energy consumption for that household. The adjustment factors account for differences in household structure, average weather, appliance ownership and dwelling size and are estimated semiparametrically.[8]

3.2 Equivalence adjustment

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 (Pachauri and Spreng, 2004; Charlier and Legendre, 2019; Berkouwer, 2020), as does housing energy efficiency (Boardman, 1991; 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 deter-

[7] 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.

[8] The method is general and can incorporate numerous control variables to match the local situation.

mine residential minimum energy needs by controlling for household and community characteristics. 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; He and Reiner, 2016). 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. Thus, we follow an alternative that does not require price data, but is conceptually similar to the above-mentioned regression approaches.

Specifically, we follow Ye et al. (2020). They derive household required energy consumption from a baseline household's energy consumption and rescale it by a household-specific adjustment factor, as in

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

where REC_i is household i's required energy consumption, i.e. the energy poverty line in our analysis; $\bar{E}$ is the baseline household's energy consumption; Λ_i represents the energy equivalence adjustment factor for household i.

Baseline energy ($\bar{E}$) is based on a reasonable living standard in South Africa. For this analysis, we assume that a reasonable standard of living requires access to electricity, as well as a stove, a refrigerator, the ability to communicate and be entertained. The approach is easily generalisable, depending on the sort of data that is available. Our data only allows us to consider a limited set of appliances. 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 baseline household size and composition. Thus, we define a baseline household to be a single (adult) person living in a medium space (between 60 and 119 m^2) in spring or fall, having a fridge and stove, being able to communicate with a cellphone and able to access entertainment through at least a TV or radio. This group will be summarised in the following section.

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 to for the aforementioned household attributes, as in

$$w(x^r, \mathbf{d}^r) = f\left(\ln x - \sum_j \lambda_j d_j^a\right) + \varepsilon, \tag{3}$$

where w denotes household energy share, vector $\mathbf{d}$ represents categorical characteristics related to household basic energy needs,[9] x is household total expenditure, superscript r refers to the reference household, superscript a refers to a non-reference household, and ε is the error term assumed to not be correlated with the other variables in the model.

The function f is estimated nonparametrically, via the np package (Hayfield and Racine, 2008) for R (R Core Team, 2020). 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 exponential of the sum of the estimates for all of the relevant characteristics (that are different

[9]Characteristics are indicators, such as having a stove or a specific number of adults or children in the household. The full set of variables and results are presented in Table 1. The baseline household, by definition, is the reference household in this regression.

from the reference household). That is,

$$\Lambda_k = \exp\left(\sum_j \lambda_{kj}\right). \tag{4}$$

4 Data description

The data used for this study come from the South Africa Living Conditions Survey (LCS) 2014/2015 (Stats SA, 2017a). The dataset contains detailed information on household expenditure, energy expenditure and a number of household-level characteristics for 22 292 households. In terms of domestic energy consumption, unfortunately, some households have consolidated water and electricity bills, which can not be separated, while some households receive free basic electricity (FBE) from municipalities/Eskom. In the LCS 2014/2015 data, 2 650 out of 22 292 (12%) households report positive values of FBE and 1 185 out of 22 292 (5%) record no spending on energy; thus, it is difficult to ascertain if FBE is directly affecting their expenditure behaviour. Hence, we only select households with zero FBE recorded, and we limit our analysis to households who have purchased positive amounts of energy.

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

Table 2 describes some of that data across income deciles. An average household spends about 7% of its budget on energy, while average total expenditure in the household is ZAR 7 593 per month (≈USD 633; 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 11%. 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 40%. As noted above, it is possible that these households are curbing their energy consumption in order to meet other priorities, and, therefore, 40% is likely to be a lower bound.

Table 2: Descriptive statistics by income decile.

Income decile	Energy expenditure (ZAR)	Electricity expenditure (ZAR)	Total expenditure (ZAR)	Energy share	Energy share > 10%
1(lower)	161.03	144.83	1919.99	0.11	0.40
2	162.36	141.40	2173.83	0.09	0.31
3	175.16	155.72	2756.11	0.08	0.24
4	203.61	181.02	3132.28	0.08	0.23
5	214.60	196.72	3756.23	0.07	0.19
6	250.13	232.20	4502.84	0.07	0.18
7	290.85	272.91	5897.93	0.06	0.14
8	369.84	350.72	8083.72	0.05	0.10
9	472.74	460.66	13652.68	0.04	0.05
10(upper)	784.04	765.10	30070.13	0.03	0.02
Total	308.40	290.09	7592.90	0.07	0.19

Household energy expenditure, electricity expenditure and total expenditure are monthly values. Energy share is calculated as the ratio between energy expenditure and household total expenditure. $N = 17\ 367$.

The summary statistics for the data used to estimate equation (3), and, thus, the equivalence adjustment in equation (4), and, finally, the REC 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, i.e., both the “Adults=3” and “Kids=2” binary variables will be set to 1, while all others will be turned off, for a household with three adults and two children. We see that more than 40% of South African households have more than two adults, while about 16% 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 basic equipment for cooking: the ownership of fridge (refrigerator or combined fridge freezer) and stove (gas, electric or paraffin). In addition, it is assumed that ownership of basic equipment for social communication (cellphone) and self-entertainment (TV or radio) helps households achieve a reasonable standard of living. According to the LCS, more than 85% of households own stoves, cellphones and self-entertainment in South African households, while the ownership of a fridge is less prevalent (70%). We further include geysers in the semiparametric model, because water heating (often by electric geysers), rather than space heating is the largest end-user of electricity in the residential department (Meyer, 2000). In addition, about 45% of South African households stay in a medium to larger size of homes (no less than 60 m^2).

5 Results and discussion

5.1 Semiparametric model

Before we can present our FGT results, we need to estimate the household adjustment factors, and then determine required energy consumption (household-specific poverty line). These factors, equivalence scales, are based on the parameter estimates arising from the semiparametric model of household energy expenditure shares. The parameter estimates are presented in Table 1. We estimate an energy equivalence scale for each household following equation (4),

Table 3: Summary statistics of major variables ($N = 17\ 367$).

Variable description	Mean	Standard deviation
Monthly household total expenditure (unit: ZAR)	7592.90	11558.54
Energy share (= actual energy expenditure/total expenditure)	0.07	0.06
Adults = 1	0.26	0.44
Adults = 2	0.33	0.47
Adults = 3	0.20	0.40
Adults = 4	0.12	0.33
Adults = 5	0.06	0.23
Adults = 6	0.03	0.16
Adults = 7	0.01	0.10
Kids (< 15-year-old) = 0	0.45	0.50
Kids = 1	0.21	0.41
Kids = 2	0.18	0.38
Kids = 3	0.10	0.29
Kids = 4	0.04	0.20
Kids = 5	0.02	0.13
Winter: survey month in May, June or July	0.25	0.43
Summer: survey month in November, December, January or February	0.35	0.48
Fridge: the household owns a refrigerator/combined fridge freezer	0.70	0.46
Geyser: the household owns a geyser	0.19	0.39
Stove: the household owns a stove (gas, electric or paraffin)	0.85	0.35
Cellphone: the household owns a cellphone	0.92	0.27
Entertainment: the household owns a TV or a radio	0.86	0.34
Estimated area of the dwelling unit:		
Very small space: less than 30 m^2	0.08	0.28
Small space: between 30 and 59 m^2	0.21	0.40
Medium space: between 60 and 119 m^2	0.29	0.46
Large space: between 120 and 239 m^2	0.13	0.33
Very large space: 240 m^2 or more	0.03	0.18
Not applicable space: the household is either not living in a permanent structure or there are multiple households living in one permanent structure.	0.26	0.44

while the required energy consumption is calculated from equation (2). However, REC is underpinned by the baseline household, which is summarised in Table 4. The baseline energy requirement is the 75^{th} percentile of energy expenditure for the baseline group, which is ZAR 199.97 per month. In addition to the baseline group, we also summarise the estimated equivalence scales and REC values in Table 4. Our estimated energy equivalence scales range from 0.63 to 2.27, while the derived REC falls between ZAR 126 and ZAR 454 per month. The mean REC, ZAR 219, is lower than the mean of actual monthly energy expenditure ZAR 308 (Table 2); although not illustrated here, monthly energy expenditure has a long tail, and, therefore, the sample mean (ZAR 308.4) exceeds the sample median (ZAR 199.91) by quite some margin.

Table 4: Descriptive statistics of semiparametric resuilts.

	Baseline group		Energy equivalence scale	Required energy expenditure
	Total expenditure	Actual energy expenditure		(unit: ZAR)
Min.	312.90	89.92	0.63	126.38
1st Qu.	1519.33	89.96	0.89	178.35
Median	2391.95	99.99	1.00	199.97
Mean	3419.91	161.28	1.10	219.46
3rd Qu.	3764.59	199.97	1.32	264.89
Max.	26946.35	797.96	2.27	454.16
Observation	85		17367	17367

Energy equivalence scale is calculated following equation (4); Required energy consumption is calculated from equation (2) as per household per month value.

5.2 Results of the FGT measures

Using the estimated household-specific energy poverty lines, we apply the FGT measures 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 income groups. As shown in the table, in total, about half of the households are energy poor, according to the headcount index (P_0), while the energy poverty gap (0.23) and severity (0.12) indexes are lower.

The income group decomposition shows us that average energy poverty rates do not increase with total income, and that is true for all three indexes. The headcount ratio ranges from a high of 78% amongst low-income households down to 11% for high-income households. And, given the 52% 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-income, as would be expected; however, the energy expenditure shortfall is approximately 38% at the bottom, but only 4% 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 income 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 income subgroups make to the total energy severity is more than that of higher income groups.[10] For policy purposes, these differing contributions help focus policy discussions. Thus, we see that further energy support to lower-income groups is warranted. We investigate some options along those lines, below.

In Table 6 we compare our results with previous estimates that are based on alternative methods. The Department of Energy (DOE, 2012, 2013) have used a 10% poverty line, such that a household is defined to be energy poor if its energy share (i.e. actual energy expenditure/total expenditure) is greater than 10%. Hence, that poverty line, like ours, is household-specific. In addition, we calculate another energy poverty line as average energy expenditure for income poor 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, 2017b). Using this definition, we calculated average energy expenditure of ZAR 170.05 per

[10] In addition, Table 2 presents decomposition of the FGT results by a few household characteristics.

Table 5: Energy poverty estimates by income group.

Income 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)	0.78	0.38	0.21	17.77
2	0.76	0.35	0.18	15.71
3	0.71	0.32	0.16	13.76
4	0.65	0.28	0.14	12.26
5	0.60	0.26	0.14	11.54
6	0.54	0.23	0.12	9.81
7	0.45	0.18	0.09	7.91
8	0.36	0.14	0.07	6.02
9	0.24	0.09	0.04	3.69
10(upper)	0.11	0.04	0.02	1.51
Total	0.52	0.23	0.12	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.

household per month.

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% poverty line probably underestimates energy poverty and (2) an energy poverty line defined within income poor households only might also underestimate energy poverty. 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, should offer more separation

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

	Poverty line[a]: 10% of total expenditure			Poverty line[b]: average energy expenditure of income poor		
Income decile	P_0	P_1	P_2	P_0	P_1	P_2
1(lower)	0.40	0.31	0.51	0.70	0.31	0.15
2	0.31	0.22	0.34	0.70	0.30	0.14
3	0.24	0.15	0.24	0.63	0.27	0.12
4	0.23	0.15	0.25	0.56	0.24	0.11
5	0.19	0.11	0.13	0.51	0.21	0.10
6	0.18	0.10	0.12	0.43	0.18	0.08
7	0.14	0.06	0.07	0.32	0.13	0.06
8	0.10	0.05	0.06	0.24	0.10	0.04
9	0.05	0.02	0.01	0.12	0.05	0.02
10(upper)	0.02	0.01	0.00	0.04	0.02	0.01
Total	0.19	0.12	0.17	0.43	0.18	0.08

[a]: For the 10% energy poverty line, a household is defined energy poor if its energy share (i.e. actual energy expenditure/total expenditure) is greater than 10%. [b]: Following Foster et al. (2000), the energy poverty line is defined as average energy expenditure for households whose overall per capita consumption level falls at or below the income poverty line of the country. We select the income poor households accordingly by the South African upper-bound poverty line (UBPL) from April 2015 - ZAR 992 per person per month (Stats SA, 2017b). Thus we are able to calculate the average energy expenditure for this group as ZAR 170.05 per household per month.

between 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.

We compare our results to previous local studies, which allows us to partially validate the methods we have adopted. Our estimates of energy poverty incidence, the easiest to compare across studies, lie within the range of estimates outlined in Table 1, although our estimates suggest more energy poverty than has been estimated by many. For example, government estimates place energy poverty at 47% in 2012 and 43% in 2013 (DOE, 2012, 2013). Our for low-income group estimates lie within the ranges available from Tait (2017) and Israel-Akinbo et al. (2018), although that research focuses only on low-income households in South Africa.

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. These additional measures account for the intensity (or depth) of energy poverty and take inequality amongst the energy poor into account, respectively.

5.3 Sensitivity analysis

For the initial analysis, we choose the 75^{th} percentile of energy expenditure for the baseline group, and, therefore, energy poverty rates are determined by that assumption. In order to get some idea about the effect of this assumption, we consider alternative assumptions, see Table 7. That table includes poverty estimates underscored by assuming both the median expenditure of the baseline group and the 90^{th} percentile of the baseline group's energy expenditure. As expected, the results presented in Table 5 lie between the ones presented in Table 7. Even assuming a poverty line based on a much lower baseline energy expenditure level – ZAR 99.99 compared to ZAR 199.97 – energy poverty is found to be an extensive problem in South Africa.

Table 7: Sensitivity analysis.

Income decile	Lower poverty line			Higher poverty line		
	P_0	P_1	P_2	P_0	P_1	P_2
1(lower)	0.35	0.09	0.04	0.91	0.54	0.36
2	0.28	0.06	0.03	0.90	0.52	0.33
3	0.24	0.05	0.02	0.88	0.48	0.30
4	0.22	0.05	0.02	0.84	0.45	0.28
5	0.22	0.05	0.02	0.81	0.42	0.26
6	0.18	0.04	0.01	0.75	0.37	0.22
7	0.15	0.03	0.01	0.70	0.32	0.19
8	0.12	0.03	0.01	0.61	0.26	0.15
9	0.08	0.02	0.01	0.47	0.18	0.09
10(upper)	0.03	0.01	0.00	0.24	0.08	0.04
Total	0.19	0.04	0.02	0.71	0.36	0.22

The lower energy poverty line is determined by the median of energy expenditure of the baseline group (ZAR 99.99), while the higher energy poverty line is determined by the 90^{th} percentile of the energy expenditure of the baseline group (ZAR 199.97).

6 A policy simulation

Given our understanding of who is energy poor and how poor they are, one can begin to 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.[11]

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-expenditure households access

[11] Recall that we did not include households with access to FBE, due to our uncertainty about whether or not energy expenditure properly captures the FBE component separate from the non-FBE component. In the LCS, 2 650 out of 22 292 (12%) households report positive values of FBE.

to 50 kWh, 100 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, the energy utility. 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, 2017)), to turn each FBE into an energy expenditure equivalent.

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 (2017b), the UBPL is ZAR 992 per person per month (about 2.76 USD per person per day). Given this value, 7 166 households out of 17 367 (41%) are defined as low-income households.

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. Table 8 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 the headcount ratio amongst poor households is estimated to fall from 70% to 8%.

Table 8: Percentage of energy poor households in each FBE policy scenario.

Indicator	No FBE	FBE = 50 kWh	FBE = 100 kWh	FBE = 150 kWh
FGT P0	0.70	0.60	0.23	0.08
FGT P1	0.31	0.19	0.07	0.02
FGT P2	0.16	0.08	0.03	0.01

FBE represents free basic electricity. Low-income households are defined to have per capita expenditure not in excess of the upper bound national poverty line (i.e., ZAR 992 per person per month). We assume a residential electricity price of 0.9806 ZAR/kWh, which was the annual average Eskom residential electricity price in 2014/2015 (DOE, 2017)). Thus, 50 kWh FBE is worth 49 ZAR, 100 kWh FBE is worth 98 ZAR, 150 kWh FBE is worth 147 ZAR. $N = 7166$.

7 Conclusion

Although energy poverty is an international concern – this can be seen in the tenets of sustainable development goal (SDG) 7 (Pachauri and Rao, 2020) – 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 (IEA, 2017). Multidimensional measures of energy poverty offer additional context, because, as the name suggests, they capture multiple dimensions (Nussbaumer et al., 2012; Charlier and Legendre, 2019). Oftentimes, such studies include a measure of affordability (Zhang et al., 2019; Tait, 2017), as well. However, such measures typically apply arbitrary weights, and, therefore, are subject to those weights, as well as the number of dimensions that are available.

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 we follow, 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. The latter two are not often available, because they require 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 an 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: (1) energy poverty is extensive in the country; (2) our estimates are reasonable, since they are within the ranges currently available in the literature; (3) thus, applying equivalence scale methods to determine an energy poverty line is not unreasonable. 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.

Declarations of interest

None.

A Semiparametric index model parameter estimates

Table 1: Semiparametric index model parameter estimates.

Variable	Scale adjustment	Standard error
Log of household total expenditure	1.0000[a]	(0.000)
Adults = 2	-0.0312[a]	(0.002)
Adults = 3	-0.0007	(0.002)
Adults = 4	-0.0232[a]	(0.002)
Adults = 5	0.0605[a]	(0.003)
Adults = 6	-0.0357[a]	(0.004)
Adults = 7	-0.0292[a]	(0.006)
Kids = 1	-0.0326[a]	(0.002)
Kids = 2	-0.0775[a]	(0.002)
Kids = 3	-0.1624[a]	(0.002)
Kids = 4	-0.0125[a]	(0.004)
Kids = 5	-0.0683[a]	(0.004)
Winter	0.0671[a]	(0.001)
Summer	0.0346[a]	(0.001)
Fridge	0.0788[a]	(0.002)
Geyser	0.3630[a]	(0.002)
Stove	-0.0844[a]	(0.002)
Cellphone	0.0017	(0.002)
Entertainment	-0.0522[a]	(0.002)
Very small space	-0.0506[a]	(0.002)
Small space	-0.1089[a]	(0.002)
Large space	-0.0075[a]	(0.002)
Very large space	0.0344[a]	(0.003)
Not applicable space	0.3123[a]	(0.002)

Parameter estimates from semiparametric least squares; see Ichimura (1993) – Significance levels: [a] - 0.005, [b] - 0.01, [c] - 0.05, [d] - 0.1.

B FGT results by province

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Table 2: Decomposition of FGT measures.

	Headcount index (P_0^k)	Energy poverty gap (P_1^k)	Energy poverty severity (P_2^k)	Percentage contribution to total P_2
Province				
Western Cape	0.34	0.14	0.07	6.80
Eastern Cape	0.63	0.29	0.15	15.27
Northern Cape	0.41	0.17	0.09	4.04
Free State	0.58	0.27	0.15	10.06
KwaZulu-Natal	0.53	0.24	0.13	17.84
North West	0.58	0.26	0.13	9.44
Gauteng	0.37	0.14	0.07	8.74
Mpumalanga	0.54	0.24	0.13	11.35
Limpopo	0.66	0.29	0.14	16.46
Settlement type				
Urban formal	0.37	0.15	0.08	34.83
Urban informal	0.66	0.31	0.17	9.95
Traditional area	0.70	0.31	0.16	49.94
Rural formal	0.54	0.28	0.17	5.29
Population group				
Black African	0.59	0.26	0.13	93.88
Coloured	0.30	0.12	0.06	5.29
Indian/Asian	0.09	0.04	0.02	0.26
White	0.08	0.02	0.01	0.56
Electrification status				
Electrified	0.49	0.21	0.10	93.35
Unelectrified	0.81	0.40	0.22	6.65
Estimated area of the dwelling unit				
Very small space	0.72	0.33	0.17	11.90
Small space	0.57	0.24	0.11	19.42
Medium space	0.50	0.21	0.11	26.67
Large space	0.31	0.12	0.06	6.47
Very large space	0.18	0.07	0.04	1.11
Not applicable space	0.58	0.27	0.16	34.43
Total	0.52	0.23	0.12	100.00

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