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Abstract

This study proposes an equivalence scale model for required energy consumption at the household level. The proposed approach equivalises actual energy expenditure across households in two steps: estimating an equivalence scale and dividing actual expenditure by the estimated scale for each household. We apply the method in a case study where data on required energy expenditure are not available. Our South African case study results suggest that the energy equivalence scale differs from both income and energy equivalence factors used in developed countries, while the choice of equivalence estimation method has limited impact on energy requirements. As expected in a middle income and highly unequal country, estimates of required energy consumption are well above actual energy expenditure for low- and mid-income households. Given the similarity of results across methods, we are further able to suggest that required energy consumption, where data are not available, can be quickly estimated from expenditure data. Required energy consumption, Equivalence scale, Energy poverty, Semiparametric regression

Keywords: Equivalence Scale, Semi-parametric, Energy Consumption

JEL classification: I31, Q40, Q48

1. Introduction

Domestic daily energy use in cooking, lighting, space heating and cooling, and water heating contributes to household well-being by providing options in meeting various household requirements, while the direct energy consumption contributes to the household budget. However, energy consumption is different from many other consumer goods, because it is often considered a basic need (Welsch and Biermann, 2017); its satisfaction is necessary for an acceptable quality of life[1]. In reality, it can be difficult to meet basic household energy need, especially in low-income households. In other words, there exists energy poverty.

Energy poverty refers to a situation wherein basic household energy need cannot be met. Measuring such poverty, however, is defined relative to basic energy need, and need is not always obvious. Common energy poverty indicators

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[1]Modern energy services such as electricity and LPG is instrumental for most of human basic needs (Chakravarty and Tavoni, 2013).

often focus on the relationship between household income and required energy consumption (REC). For example, the energy poverty ratio (EPR) defines a ratio of theoretical (i.e., required or modelled) energy expenditure to income, while the low-income-high-cost (LIHC) indicator defines an energy consumption threshold based on household REC. The crucial feature of these indicators is that they reply on basic energy need or required energy, which is unknown. Thus, in application, actual energy expenditure is often used instead of required household energy expenditure (Mohr, 2018; Heindl, 2015; Legendre and Ricci, 2015), possibly leading to underestimates of energy poverty, because some households may limit their energy consumption to meet other needs. Such an approach could also overestimate need, if households are purchasing an inordinate amount of electricity for nonessential consumption. Although there may be over- and underestimation issues arising from the use of actual energy expenditure, actual expenditure is the only information that is widely available in developing countries.

Rather than using actual energy expenditure, another option is to use energy models and residents' basic living standards to estimate REC. In Greece, Papada and Kaliampakos (2018) model energy consumption at household level and then transfer from household level to country level through stochastic analysis (Monte-Carlo simulation). Their stochastic model relies on aggregated domestic energy consumption data rather than household level survey data, and, therefore, cannot address household heterogeneity, which is likely to influence household basic energy requirements. Ntaintasis et al. (2019) offer an approach that is able to address household heterogeneity. They consider floor area, type of residence, age of residence, energy prices and annual specific electrical and thermal energy consumption required across different types of Greek residential buildings to estimate REC for each household; their research is built upon their own survey, and, therefore, may not be easily replicable in many developing country contexts.

In the United Kingdom (UK), a detailed Building Research Establishment Domestic Energy Model (BREDEM) is developed (BRE, 2015), which estimates REC based on dwelling and household characteristics[2]. Based on the detailed dwelling and household information provided by the English Housing Survey, the BREDEM model calculates total household energy requirements for space and water heating (to meet defined standards), energy for lights and appliances (including requirements for pumps, fans and electric showers, and energy generated by renewables), and energy for cooking (BEIS and BRE, 2018). Once required energy usage has been determined, it is multiplied by the relevant energy price to derive REC. The complexity of the BREDEM equations makes it sensitive to the values of multiple parameters. In a recent review, Herrero (2017) shows that actual energy expenditure is well below (BREDEM) modelled energy expenditure, even in higher income deciles. Such results imply that wealthy households in the UK are energy poor, which is difficult to reconcile with its developed country status. These results might even suggest that overestimation of household energy requirements is possible under the BREDEM model, limiting its value and generalisability in application. Thus, even if such models were plausible for developing country contexts, questions would remain about their accuracy. However, as can be seen from the discussion, energy modelling requires consid-

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[2]Required heat energy, for example, will depend on building specifications, such as: insulation levels, heating systems, geographical location of the dwelling and construction type. The household's energy demand will depend on the number of people, as well as the lifestyle and habits of these individuals.

erable engineering expertise and real time energy usage data for model development and calibration, while resident living standards may not be readily available for consumers dispersed over large geographical locations. In other words, such models require extensive data, and therefore, may not be plausible in developing countries.

Apart from difficulties related to the estimation of REC, one must also address heterogeneity across households, i.e., adjust energy requirements to account for family size and composition, such that households can be reasonably compared when determining energy poverty. However, equivalisation of household energy consumption for energy poverty indicators is uncommon. Normally it is ignored or assumed to be the same as typical income equivalence factors (Herrero, 2017; Hills, 2011). For example, Legendre and Ricci (2015) apply the OECD-modified income equivalence scales to adjust household income for the EPR calculation, but there is no equivalisation of energy expenditure[3]. The OECD-modified scale, first proposed by Hagenaars et al. (1994), assigns a value 1 to the household head, 0.5 to each additional adult member, and 0.3 to each child (under 14 year-old). As acknowledged by Hills (2011), the OECD income equivalence factors do not reflect how energy requirements vary between households, as the additional energy spending required to take account of each additional member of the household would not be the same as the additional amount of income required for additional household members to maintain an overall standard of living.

Instead, Hills (2012) proposes equivalisation factors for the modelled energy bills underpinned by the three years data of the English Housing Survey[4]. The equivalisation factors are calculated from ratios between median required household energy expenditure within different household groups and median required energy expenditure in two-adult households. These same equivalisation factors are applied in other developed countries as well. Heindl (2015) estimates the German energy poverty rate using the UK median to median ratio scales; the scales are used to equivalise actual energy expenditure rather than required, which is not observed in the German data. Such scales offer a convenient way to equivalise energy consumption; however, they should be based on REC.

As can be seen from the above literature, energy equivalence scales are primarily derived from developed world experience, and, therefore, may not be appropriate for the developing world.

More generally, equivalence scales are used for welfare analysis to compare household well-being, although such scales are not perfect (Pollak and Wales, 1979). One common scale is the per capita scale; for example, country welfare is often inferred from gross domestic product (GDP) per capita comparisons. Similarly, expenditure (or income) per capita is a common welfare proxy. However, per capita expenditure ignores household economies of scale in consumption, which refers to the notion that some goods and services consumed by the household have public good characteristics: they generate benefits for household members apart from the primary consumer (Nelson, 1988; Lazear and Michael, 1980). Domestic energy consumption has household public good characteristics. Lazear

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[3]A brief description of the equivalence scales used by the Organisation for Economic Co-operation and Development (OECD) is shown in www.oecd.org/els/soc/OECD-Note-EquivalenceScales.pdf.

[4]According to BEIS and BRE (2018), the UK's equivalisation factors are based on three years of required energy expenditure data from the English Housing Survey (using the 2008, 2009 and 2010 datasets). The combined three year weights were used to arrive at the final equivalisation factors. During the calculation, adults and children are treated equally in the equivalisation of modelled bills - that is, a household with two adults and two children are treated the same as a household with four adults. In addition, the equivalisation factors are not intended to be reviewed on an annual basis.

and Michael (1980) suggest that "electric light in a room" is one such example. Energy used to light an area is not completely dependent on the number of people in that area, which is also true for energy used for cooking and space heating/cooling. As argued by Nelson (1988), sharing of goods could lead to a decrease in the per capita cost of maintaining a standard of living. Thus, the proportionate increase in energy expenditure for these services is less than the increase in household numbers. In addition, energy requirements could be age or gender specific, because both young children and the elderly are more sensitive to abnormal weather, and thus they may require more energy in that case. Therefore, it is reasonable to use a more nuanced equivalence scale, one that accounts for household size and structure, rather than a per capita equivalence scale. Below, we propose an alternative solution. The intuition we apply is similar in nature to the principle behind the scale proposed by Hills (2012) and even the OECD's equivalisation factors, although we do not begin by specifying an exact point in the energy expenditure distribution (Hills, 2012), or base our estimates on total household income (OECD).

Methodologies for equivalence scale estimation have been developed over decades, although much work remains. The initial impetus for scales comes from Engel (1895), who argues that since richer households spend a smaller share of the household budget on food, the share of the household budget allocated to food is a reasonable measure of household welfare. An Engel income equivalence scale, derived from Engel's welfare argument, is defined as the ratio of two household incomes: each having the same food budget share, but each having different household sizes and structures (Lewbel and Pendakur, 2008). Typically, a single-person adult or two-person adult (no children) will serve as a reference household for the welfare comparisons. Nicholson (1976) argues, however, that Engel type income equivalence scales are likely to overestimate the cost of a child, because they do not treat child goods separate from adult goods and because child costs, especially when young, are primarily food costs. Xu et al. (2003) simplify the entire discussion, arguing that the equivalisation factor is the elasticity of food expenditure with respect to household size[5]. Such an assumption simplifies the estimation of equivalence scales, because it ignores household expenditure, implicitly assuming it is uncorrelated with household size, which may not be a realistic assumption. Since larger household tends to spend more on food in total, exclusion of household expenditure potentially yields biased estimates (Koch, 2018). In terms of domestic energy consumption, the relationship between total energy expenditure and household size might differ due to its public good characteristics. Therefore, we modify the Xu et al. (2003) method by including household expenditure to estimate energy equivalence scales. The preceding methods are implicitly linear in nature, and do not account for nonlinearities that might arise. The methods further do not account for base-independence, which requires the equivalence scale to remain the same for all levels of utility, such that it cannot depend on expenditure (see Pendakur, 1999, for further details). Thus, we also consider a semiparametric model proposed by Yatchew et al. (2003) that imposes base-independence, although we also modify it to focus attention on energy expenditure.

Below, we propose equivalence scale required energy consumption (EqSREC) as a reasonable option for estimat-

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[5]The usual Engel method uses the food share as the outcome variable, and, therefore, directly includes household expenditure.

ing REC, especially when detailed energy modelling and usage data are not available. As the name suggests, the method requires the estimation of an energy equivalence scale, which is then used to rescale actual energy expenditure for the household. We consider a number of possible scales, modified from the energy and economics literature, although we do not suggest our list is exhaustive. Most importantly for applied energy research, the methods are fairly easy to apply. The EqSREC approach has the following features:

- It is a regression-based approach requiring only household energy expenditure and household size and structure data, which are readily available in budget (income and expenditure) surveys around the world.

- It clarifies the process for estimating energy consumption equivalence scales.

- The EqSREC method can be used to determine subsistence energy expenditure, which will be useful for energy poverty measurement and energy poverty indicators.

We apply the EqSREC in a case study of South Africa. In our case study, the estimated REC for low- and mid-income groups are well above actual energy expenditure, which is intuitively appealing. South Africa is an unequal country, where poverty is rife (Leibbrandt et al., 2016). Thus, we would expect poor households to require more energy than they are currently using. Although we do not find the scales to be the same across methods, we do not see those scale differences impacting the final REC in an important way, at least in our case study. However, results might vary by case, and, therefore, we believe it is important to present the alternative scale estimators. Thus, at least in our case study, the choice of equivalence scale estimation method has little impact on the resulting REC.

The remainder of this paper is organised as follows. Detailed procedures of the proposed EqSREC approach is described in Section 2. We discuss the South African case study in Section 3 and present the results and discussion in Section 4. Section 5 concludes.

2. Methods

In order to estimate REC, we modify the method of Xu (2005). In our modification, we normalise actual household energy expenditure using estimated equivalence scales; our normalisation yields required energy expenditure. Thus, our contribution is to offer a straightforward process for determining required energy expenditure using readily available information on actual energy expenditure of the household.

2.1. Modelling required energy consumption

Initially, we determine equivalisation factors or equivalence scales. Then, we use these scales, along with actual household energy consumption, to determine a subsistence level of equivalent consumption. Finally, subsistence energy consumption is multiplied by equivalent household size to determine the household's required energy consumption. The steps are outlined as follows.

Step 1: Estimate equivalence factors. The equivalence factors are estimated to address heterogeneity across households related primarily to household structure, which is an important determinant of energy need. A number of options are available to address the household heterogeneity. For example, we could simply divide by the size of the household, such that our scale would be a per capita scale. In this analysis, however, we allow the data to define the scale, and we describe a number of estimation methods for determining the scale in more detail below. At this point, an equivalence scale, ES_i, is estimated for each household i.

Step 2: Equivalise actual household energy expenditure. Once obtaining an adjustment factor for the household, we calculate the equivalent energy expenditure as the ratio of actual energy expenditure to the equivalent scale. Our scale is an adjustment factor with reference to a single-adult (see below), we will refer to this ratio, $E_{eqv,i}$, as energy expenditure per adult equivalent.

$$E_{eqv,i} = \frac{E_i}{ES_i}, \tag{1}$$

where E_i is actual energy expenditure of household i, and ES_i is the estimated energy consumption equivalence scale.

Step 3: Determine subsistence energy expenditure. Defining w_i as the energy expenditure share of total household expenditure, we pull out the middle 10% of the w_i distribution (i.e., the observations between the 45th and 55th percentile) and calculate a weighted average of $E_{eqv,j}$ for all j observations in the middle 10% of the distribution. The weighted average $\bar{E}_{eqv}$ is "expected" per adult equivalent subsistence expenditure.

$$\bar{E}_{eqv} = \frac{\sum_{j=1}^{m} \Omega_j E_{eqv,j}}{\sum_{j=1}^{m} \Omega_j}, \tag{2}$$

where m represents the number of observations in the middle 10% of the distribution of w_i, and Ω_j is the survey weight for household j, $j \in [1, m]$.

Step 4: Estimate REC for each household. Each adult equivalent in the household is assumed to need the subsistence level of energy; therefore, required household energy consumption is the number of adult equivalents in the household multiplied by the subsistence level.

$$E_{req,i} = \bar{E}_{eqv} \times ES_i, \tag{3}$$

where $E_{req,i}$ is the REC of household i.

2.2. Methods to estimate equivalence factors

As outlined above, an important component of our EqSREC process is the equivalence scale. In order to estimate an equivalence scale a number of assumptions need to be considered. Although the details are described more fully

Table 1: Comparison of three equivalence scale estimation methods

Method	Dependent variable	Independent variable	Pros and Cons
Log-linear expenditure model	Energy expenditure	Household size and total household expenditure	- Linear model, easy to apply; - Considers family size; ignores structure; - Does not capture nonlinear effects; - Ignores base-independence.
Linear Engel curve	Energy share	Household size and structure, total household expenditure	- Linear model; - Considers family size and structure; - Ignores base-independence.
Semiparametric Engel curve	Energy share	Household size and structure, total household expenditure	- Nonlinear model, captures nonlinear effects; - Relatively more time-consuming to estimate; - Considers family size and structure; - Imposes base-independence.

below, our primary assumptions are that household basic energy need is determined by family size and, possibly, composition. Despite the simplifying assumptions that only household size and composition matter, a number of alternative estimation strategies are available for estimating the underlying scale. In this analysis, we apply three different methodologies and offer a comparison between them. Two of these methods are linear in nature, while the third is nonlinear. We outline pros and cons of the methods in Table 1, but point the reader to the separate subsections for more details about the methods.

2.2.1. Log-linear expenditure model

The first method considered is based on a linear regression model proposed by Xu et al. (2003) which has been used extensively in the health economics literature (see Koch, 2018, for example). Given the fact that larger households may require more energy for domestic use and ignoring total household expenditure in the model may overestimate the effect of household size, we consider a revision of the Xu et al. (2003) and Xu (2005) method. We use (the natural log of) actual energy expenditure as the dependent variable, and include (the natural log of) household size and (the natural log of) household expenditure as the independent variables to estimate an equivalence scale parameter θ,

$$\ln(E_i) = \alpha_0 + \theta \ln n_i + \beta_0 \ln x_i + \epsilon_0, \tag{4}$$

where E_i is actual energy expenditure in household i, n_i is household size, x_i is total household expenditure and ϵ_0 is an error term, assumed to not be correlated with household size. The estimated parameter θ is used to determine the

equivalence adjustment, which is an exponential function

$$ES_{log,i} = n_i^\theta. \tag{5}$$

We take single adult households as our reference category, so the scale is equal to 1 when $n_i = 1$. For $n_i > 1$, $ES_{log,i}$ is a monotone increasing function, as long as $\theta \neq 0$. Otherwise, when $\theta > 0$, $ES_{log,i} > 1$, and when $\theta < 0$, $0 < ES_{log,i} < 1$.

2.2.2. Linear Engel curve

Another common approach to the analysis of equivalence is based on insight from Engel (1895), that household welfare can be described by the share of the household's budget devoted to food. In Engel's analysis, wealthier households spend smaller proportions of their budget on food than do poorer households, suggesting that welfare is decreasing in the share of food expenditure. Thus, if the food share is a reasonable welfare proxy, one could ask how much additional money would be needed by the household to reach the same level of welfare (expenditure share) as some "reference" household. Comparing one household's income (inclusive of the added amount) to the reference household's income, as a ratio, determines the scale (Deaton, 1987).

For our analysis, we extend this logic to energy consumption. We assume that household welfare can be proxied by the share of the budget devoted to energy consumption; below, we show that this measure of welfare is also decreasing in income. Thus, we use the energy share (rather than food share) as a welfare proxy and control for household structure (i.e., number of adults and children) to estimate the following model, outlined in Deaton (1987).

$$w_i = \alpha_1 + \beta_1 \ln \frac{x_i}{n_i} + \lambda \ln n_i + \gamma \frac{K_i}{n_i} + \epsilon_1, \tag{6}$$

where w_i represents the share of the budget devoted to energy consumption, x_i is total household expenditure, n_i is household size, and K_i is the number of children (we use age less than 15 to define a child) in household i, and ϵ_1 is an error term assumed not to be correlated with expenditure or household structure variables.

Although (6) is straightforward to estimate, it does not provide a direct estimate of the scale parameter, as is the case for the model in (4). Instead, the scale has to be calculated from the regression results. We begin by denoting a reference group with the r superscript. We compare energy shares in a nonreference household with those in the reference household in order to determine the income that would be needed to "equate" welfare. We begin by setting $w_i = w^r$, which yields

$$\alpha_1 + \beta_1 \ln \frac{x_i}{n_i} + \lambda \ln n_i + \gamma \frac{K_i}{n_i} = \alpha_1 + \beta_1 \ln \frac{x^r}{n^r} + \lambda \ln n^r + \gamma \frac{K^r}{n^r}. \tag{7}$$

We rearrange (7) to determine the relative income ratio, the equivalence scale:

$$ES_{d,i} = \frac{x_i}{x^r} = \exp\left\{\frac{\lambda - \beta_1}{\beta_1}(\ln n^r - \ln n_i) + \frac{\gamma}{\beta_1}(\frac{K^r}{n^r} - \frac{K_i}{n_i})\right\}. \tag{8}$$

Rearranging further, the equivalence scale is determined by the relative sizes of the household, as well as the relative adult/child make-up of the household, along with estimates from (6):

$$ES_{d,i} = \frac{x_i}{x^r} = \left(\frac{n^r}{n_i}\right)^{(\lambda - \beta_1)/\beta_1} \exp\left\{\frac{\gamma}{\beta_1}\left(\frac{K^r}{n^r} - \frac{K_i}{n_i}\right)\right\}. \tag{9}$$

Since the scales in (9) are calculated from estimates, in order to determine the variability of these scales, they must be bootstrapped. We initially estimate the scales. Then, we create 399 bootstrap resamples, from which we re-estimate (6) and re-calculate (9). The standard deviation from the resampled calculations determines the variability in the scales.

2.2.3. Semiparametric Engel curve

Each of the preceding models is underpinned by linearity assumptions. The initial regression assumes, even further, that household structure is not a relevant feature (only size), when determining equivalence. Linear models may not capture the true variability in the data that a nonlinear model can capture, and, therefore, a nonlinear comparator model is useful. Furthermore, neither of the previous models account for base-independence, the idea that the estimated scale should not be related to household expenditure (see Pendakur, 1999, for further details). Thus, we also estimate an Engel-type scale enforcing base-independence, following Yatchew et al. (2003). Using r to denote a reference household, as before, we again equate shares across household types; this semiparametric method yields a direct estimate of the equivalence scale. To incorporate base-independence, we assume any differences between shares are unrelated to household expenditure, and are likely to be simple linear translations, denoted by $\eta(p)$.

$$\begin{aligned} w(p, x^r, z^z) &= w(p, x, z) + \eta(p) + \epsilon_2 \\ &= w(p, \frac{x}{\Theta(z)}) + \eta(p) + \epsilon_2. \end{aligned} \tag{10}$$

As before, w is the energy share of total household expenditure and x is total household expenditure. In the last line of (10), we have reframed expenditure as the ratio of nonreference expenditure and the equivalence scale $\Theta(z)$, which is assumed to be a function of z (nonreference family structure). We further denote p as the energy price, which we do not have access to, while the linear translation, η, is the elasticity of the equivalence scale with respect to the price of energy. We further assume ϵ_2 is not correlated with the other variables in the model.

Because we do not have price data, we further simplify the model as

$$w(x^r, z^r) = w\left(\frac{x}{\Theta(z)}\right) + \epsilon_2. \tag{11}$$

The model in (11) is nonlinear, and is a function of only x and z. Simplifying Yatchew et al. (2003), we rewrite (11) as a single index model, where the function f is not known, and $X = \ln x - z\delta$,

$$\begin{aligned} w(x^r, z^r) &= f(X) + \epsilon_2 \\ &= f(\ln x - z\delta) + \epsilon_2. \end{aligned} \tag{12}$$

Rather than using difference procedures for estimation, as suggested by Yatchew et al. (2003), we leverage bandwidth procedures. Given the continuous dependent variable in our analysis, we implement Ichimura's (1993) method to estimate the bandwidth and coefficient vector. Ichimura's (1993) method jointly minimizes a leave-one-out nonlinear least-squares cross-validation function with respect to the parameters and bandwidth. Note that the first element of the coefficient vector is equal to one, and is required for identification. Our estimation method is implemented via the nonparametric package (Hayfield and Racine, 2008) for R (R Core Team, 2019)[6].

We undertake a series of k regressions. In each, we include our reference household group and one nonreference household group. Thus, we estimate (13),

$$w_k(x, z) = f(\ln x - z\delta_k) + \epsilon_2, \tag{13}$$

where z is a dummy variable equal to one for the nonreference household group and 0 for the reference household group, and δ_k is an estimate of the proportional or scale adjustment needed to equate energy shares in the nonreference group to energy shares in the reference group.

From these estimates, the resulting equivalence scales are

$$ES_{sp,k} = e^{\delta_k}, \tag{14}$$

and the variability of the equivalence scale estimate can be determined by the delta method (or bootstrapping). We apply the delta method.

3. Case study and data

We apply the above methods to a case study in South Africa. Our analysis is based on data from a recent household expenditure survey, the Living Conditions Survey (LCS) 2014/2015 (Stats SA, 2017). The LCS aims to provide data

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[6]Code for all of the analysis is available from the authors upon request.

that will contribute to a better understanding of living conditions and poverty in South Africa and is meant to be used for monitoring levels of poverty over time. Importantly, the survey contains information on household expenditure, energy expenditure and household size and structure, which fit our empirical models. The survey took place over a period of twelve months, so all reported expenditures were inflated/deflated to April 2015, the midpoint of the survey year using the consumer price index (CPI). The LCS follows multi-stage stratified random sampling; thus, each response comes with a weight, defined at the level of the household, that can be used to create population relevant statistics.

The LCS uses classification of individual consumption by purpose (COICOP) categories. Under COICOP, energy expenditures lie in Category 04. All expenditures on COICOP Category 045 are coded as energy sources, which includes spending/values on electricity (including conventional metering electricity and prepaid electricity), gas (including refilling gas and gas in cylinders), liquid fuels (including paraffin, petrol and diesel for household use, not transport use), solid fuels (including bought and fetched firewood, charcoal, candles, coal, bought and fetched dung, and crop waste), and other household fuel. Total energy expenditure includes expenditure from all of these energy sources. The energy share is the share of the household budget devoted to energy consumption. We use consumption expenditure instead of income for all the estimates in the analysis[7]. Household consumption expenditure comprises both monetary and in-kind payment on all goods and services, and the money value of the consumption of home-made products. Hence, the energy share equals the energy expenditure divided by total household expenditure.

The expenditure on COICOP category 0440 is coded as "water and electricity", which is for households with consolidated water and electricity bills. Since it is not possible to split electricity out of the bill, these households are ignored in the case study. In addition, there are some households receiving free basic electricity (FBE) from municipalities/Eskom[8]. Since it is hard to clarify whether the household records electricity expenditure inclusive or exclusive of FBE, and it is also hard to clarify if FBE is directly affecting their expenditure behaviour, we only select households with zero FBE recorded, and we limit our analysis to households who have purchased positive amounts of energy.

Equivalence requires information on household size and structure, such as the number of adults and children in each household. However, the semiparametric method we employ is not entirely stable, when there are less than 15 nonreference observations. Therefore, we further limit the data to households with no more than seven adults and no more than five children. Eventually, 18 038 observations remained from the initial 22 292 for the analysis.

Before turning to the analysis, we present summary information from our data. We begin with Table 2, which includes descriptive statistics for the variables used in this study. As we can see from the table, the average household spends about 7% of its budget on energy and it has one child and 2.5 adults. Average total expenditure in the household

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[7]In developing countries, it is more practical to use consumption rather than income, because formal employment is less common, many households have multiple and continually changing sources of income, and home production is more widespread. Hence, it is generally easier to measure consumption than income (Deaton and Grosh, 2000).

[8]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. Please see Ye et al. (2018) for more information about the FBE policy in South Africa.

Table 2: Descriptive statistics of the LCS 2014/2015 data

	Mean	Standard deviation
Monthly household energy expenditure (unit: ZAR)	310.38	350.98
Monthly household total expenditure (unit: ZAR)	7655.49	11575.29
Energy share of household budget	0.07	0.06
Household size	3.63	2.19
Number of children (under 15 years old)	1.10	1.28
Number of adults	2.52	1.37
Monthly electricity expenditure (unit: ZAR)	292.05	343.25
Monthly gas expenditure (unit: ZAR)	4.81	53.01
Monthly liquid fuel expenditure (unit: ZAR)	7.65	46.89
Monthly solid fuel expenditure (unit: ZAR)	5.87	48.40
Monthly paraffin expenditure (unit: ZAR)	6.83	33.85
Monthly wood expenditure (unit: ZAR)	1.78	33.14
Observation	18038	

Note: 1) Household energy expenditure includes spendings on electricity, gas, liquid and solid fuels; 2) Electricity expenditure includes the spendings on conventional metering electricity and prepaid electricity; 3) Gas expenditure including refilling gas and gas in cylinders(including gas for heating purposes); 4) Liquid fuel expenditure including spendings on paraffin, petrol and diesel (petrol and diesel for household use only, not transport use); 5) Solid fuel expenditure including firewood bought and fetched, charcoal, candles, coal, dung bought and fetched, crop waste, and other household fuel. 6) Wood expenditure including bought and fetched firewood values.

Table 3: Distribution of family types

	Number of children						
Number of adults	0	1	2	3	4	5	Total
1	3497	492	369	161	56	19	4594
2	2636	1400	1171	509	162	48	5926
3	1214	942	773	444	163	68	3604
4	562	604	505	294	170	68	2203
5	212	258	241	163	110	58	1042
6	69	113	114	94	64	24	478
7	21	36	46	46	22	20	191
Total	8211	3845	3219	1711	747	305	18038

is ZAR 7 655 per month (USD 643; 1 ZAR = 0.084 USD, April 2015). More than 94% of total energy expenditure is devoted to electricity consumption, such that electricity is the main fuel for domestic daily usage. However, average household size masks extensive heterogeneity in household structure. Table 3 outlines the distribution of family types, showing us that there are approximately 3 500 reference households, as well as a relatively large number of households with more than four adults.

The final descriptive information we present relates to the relationship between total expenditure and the share of energy expenditure. We illustrate this relationship from fitted nonparametric regressions for selected family types; see Figure 1. The relationship that we see is negative, suggesting that the extension of Engel's model to energy shares is realistic. We also see that the underlying relationship would not generally be described as linear, which suggests that the semiparametric equivalisation method is more appropriate in this setting. Finally, we see these curves lying

Figure 1: Household energy share and monthly total expenditure by family types
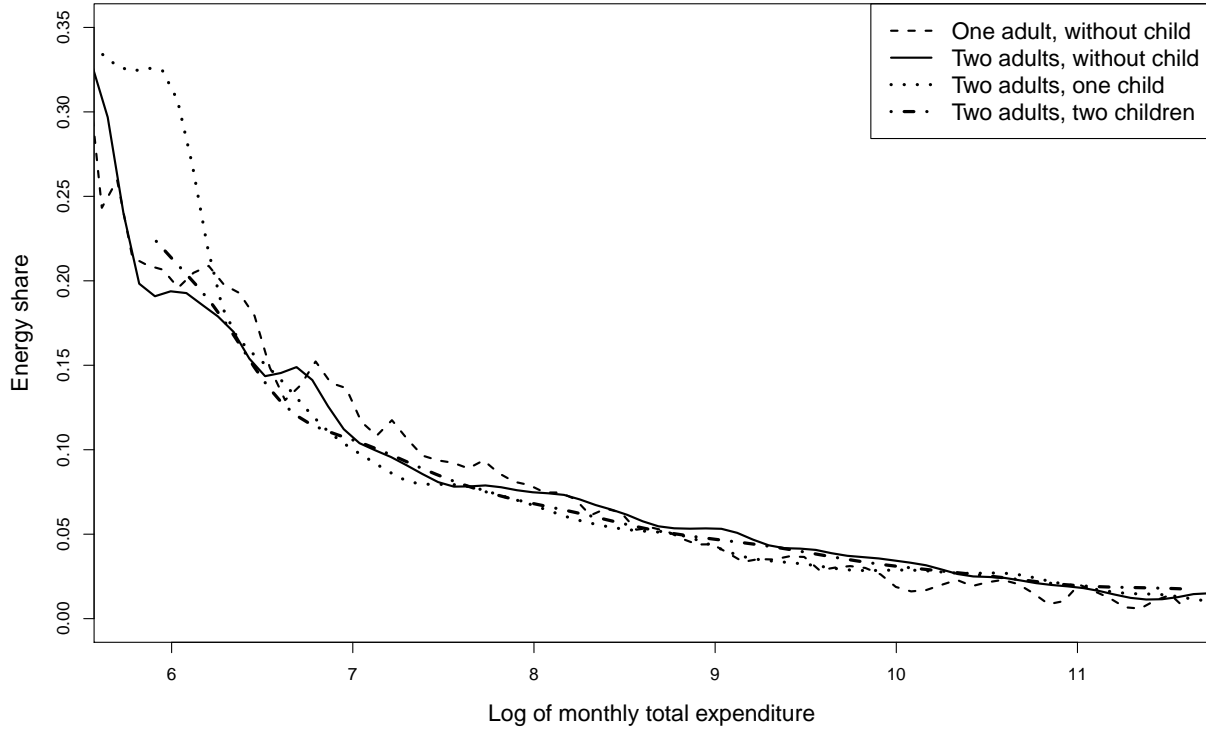
fairly close to each other, which means that, even though we do not have price data, there does not appear to be much translation from one curve to the next; in other words, assuming $\eta = 0$, as implied by (12), is reasonable.

4. Results and discussion

4.1. Energy equivalence estimates

Table 4 presents the estimates of energy equivalence scale for each of three methods. $ES_{log,i}$, the equivalence scale by the log-linear expenditure model, follows equation (5); $ES_{d,i}$, the equivalence scale by linear Engel curve, is estimated from equation (9); and $ES_{sp,k}$, the equivalence scale by semiparametric Engel curve, is from equation (14). As can be seen in the table, the energy equivalence estimates from all three methods are mostly less than one, and increased household size is generally associated with a decreased equivalence scale. The results suggest that there are extensive economies of scale in residential energy consumption, as the scales are not equal to actual household size. More importantly, the energy equivalence estimates are dissimilar to those reported for the UK [9], as well as the

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[9] According to BEIS and BRE (2018), the UK's energy equivalence factors range in (1.22-1.61) with one-adult households as the reference group.

OECD's income equivalence scale. This significant difference arises from the public good characteristics of domestic energy consumption. Sharing energy within a household could reduce the need to purchase individual allocations for each family member. Further, as shown in Table A1 and Figure 1, households are not raising their energy spend share, when family size increases, especially with increasing number of children.

The results in Table 4 also suggest that energy equivalence scales vary with the estimation method, although the disparity is minimal. For the log-linear regression model, the equivalence scale estimates decrease with increased household size. These arise from the regression results reported in Table A2, where the elasticity of household size to total energy expenditure is rather small and negative (-0.06). After incorporating family structure, estimated scales following the linear Engel curve (column 5 of Table 4) show a steeper downward gradient across increased household size (number of children or adults) than those from the log-linear model, which is consistent with the regression estimates in Table A3. As shown in Table A3, increasing household size results in a decrease in the energy share, as does the proportion of children in a household. For the semiparametric method (column 6 of Table 4), the scale estimates fluctuate, meaning there is not an increasing or decreasing trend. This results from the pairwised estimation process applied in the semiparametric method. As discussed in subsection 2.2.3, we pair the reference household group with each nonreference group to estimate the scale. For each pair, the estimate depends on the observations within the nonreference group; thus, it is not directly connected to other nonreference groups. In addition, a few scales are greater than one, especially for the pairs (adults, children) – (5,0), (5,1), (6,1), (7,0), (7,1) and (7,4).

The ranges (0.87, 0.96) for the log-linear expenditure model, (0.46, 0.89) for the linear Engel curve method and (0.62, 1.13) for the semiparametric method suggest that the estimates from the semiparametric method lie between those of the log-linear model and the linear Engel curve. The semiparametric model may be more appropriate for energy equivalence scale estimation, since it assumes base-independence. Also, it does not presume a functional form for equivalence scale estimation. However, the semiparametric method is relatively complicated and requires more time-consuming computation. When referring to the limited impact of equivalence scales on REC estimation in following section, the log-linear expenditure model is computationally easier to apply and is much more preferred. Given the limited impact of equivalence scales on our REC calculations (see below), along with the log-linear model's computational simplicity, we prefer that method for our data.

Table 4: Estimates of energy equivalence scale from three methods

Household size	Number of adults	Number of children	Log-linear expenditure model ($ES_{log,i}$)	Linear Engel curve ($ES_{d,i}$)	Semiparametric Engel curve ($ES_{sp,k}$)
1	1	0	1.0000	1.0000	1.0000
			(0.000)	(0.000)	(0.000)
2	1	1	0.9618	0.6692	0.9425
			(0.005)	(0.018)	(0.021)
3	1	2	0.9401	0.5683	0.7699
			(0.007)	(0.020)	(0.022)
4	1	3	0.9251	0.5162	0.8460

Household size	Number of adults	Number of children	Log-linear expenditure model ($ES_{log,i}$)	Linear Engel curve ($ES_{d,i}$)	Semiparametric Engel curve ($ES_{sp,k}$)
			(0.009)	(0.021)	(0.036)
5	1	4	0.9135	0.4831	0.8782
			(0.011)	(0.021)	(0.040)
6	1	5	0.9042	0.4596	0.9893
			(0.012)	(0.022)	(0.129)
2	2	0	0.9618	0.8890	0.9525
			(0.005)	(0.017)	(0.020)
3	2	1	0.9401	0.6868	0.8973
			(0.007)	(0.016)	(0.026)
4	2	2	0.9251	0.5950	0.9869
			(0.009)	(0.019)	(0.027)
5	2	3	0.9135	0.5412	0.8464
			(0.011)	(0.020)	(0.025)
6	2	4	0.9042	0.5053	0.6420
			(0.012)	(0.021)	(0.029)
7	2	5	0.8964	0.4791	0.8220
			(0.013)	(0.021)	(0.062)
3	3	0	0.9401	0.8299	0.8483
			(0.007)	(0.026)	(0.020)
4	3	1	0.9251	0.6858	0.9028
			(0.009)	(0.021)	(0.021)
5	3	2	0.9135	0.6064	0.7214
			(0.011)	(0.021)	(0.023)
6	3	3	0.9042	0.5554	0.7923
			(0.012)	(0.022)	(0.021)
7	3	4	0.8964	0.5196	0.9803
			(0.013)	(0.022)	(0.037)
8	3	5	0.8897	0.4927	0.6405
			(0.013)	(0.022)	(0.047)
4	4	0	0.9251	0.7904	0.9264
			(0.009)	(0.031)	(0.031)
5	4	1	0.9135	0.6793	0.9520
			(0.011)	(0.026)	(0.031)
6	4	2	0.9042	0.6106	0.9721
			(0.012)	(0.024)	(0.035)
7	4	3	0.8964	0.5635	0.6188
			(0.013)	(0.024)	(0.020)
8	4	4	0.8897	0.5290	0.9583
			(0.013)	(0.024)	(0.065)
9	4	5	0.8838	0.5024	0.9700
			(0.014)	(0.024)	(0.059)
5	5	0	0.9135	0.7610	1.0403
			(0.011)	(0.034)	(0.073)
6	5	1	0.9042	0.6712	1.0507
			(0.012)	(0.029)	(0.040)
7	5	2	0.8964	0.6111	0.9243
			(0.013)	(0.027)	(0.038)
8	5	3	0.8897	0.5679	0.8910
			(0.013)	(0.026)	(0.032)
9	5	4	0.8838	0.5351	0.9119
			(0.014)	(0.026)	(0.084)
10	5	5	0.8786	0.5093	0.7846
			(0.015)	(0.026)	(0.056)

Household size	Number of adults	Number of children	Log-linear expenditure model ($ES_{log,i}$)	Linear Engel curve ($ES_{d,i}$)	Semiparametric Engel curve ($ES_{sp,k}$)
6	6	0	0.9042	0.7378	0.7224
			(0.012)	(0.037)	(0.036)
7	6	1	0.8964	0.6628	1.0422
			(0.013)	(0.032)	(0.055)
8	6	2	0.8897	0.6097	0.8759
			(0.013)	(0.030)	(0.056)
9	6	3	0.8838	0.5700	0.8916
			(0.014)	(0.029)	(0.054)
10	6	4	0.8786	0.5391	0.8455
			(0.015)	(0.028)	(0.059)
11	6	5	0.8739	0.5142	0.9430
			(0.015)	(0.027)	(0.071)
7	7	0	0.8964	0.7188	1.0068
			(0.013)	(0.039)	(0.170)
8	7	1	0.8897	0.6545	1.0448
			(0.013)	(0.035)	(0.120)
9	7	2	0.8838	0.6071	0.8977
			(0.014)	(0.032)	(0.077)
10	7	3	0.8786	0.5706	0.9349
			(0.015)	(0.031)	(0.103)
11	7	4	0.8739	0.5415	1.1315
			(0.015)	(0.030)	(0.173)
12	7	5	0.8697	0.5177	0.8461
			(0.016)	(0.029)	(0.077)

Note: 1) $ES_{log,i}$, equivalence scale by log-linear expenditure model, is estimated from equation (5). 2) $ES_{d,i}$, equivalence scale by linear Engel curve, is estimated from equation (9). 3) $ES_{sp,k}$, equivalence scale by semiparametric Engel curve, is estimated from equation (14). 4) For both log-linear model and semiparametric regression, Delta method standard errors are in parentheses. For linear Engel curve, bootstrapped standard errors are in parentheses.

4.2. Estimates of required energy consumption

Recall that REC is the product of energy equivalence scales and subsistence energy expenditure (see equation (3)). Since the energy equivalence is estimated from three methods, there are corresponding estimates of REC and subsistence energy expenditure presented in Table 5. Table 5 shows that subsistence energy expenditure lies between ZAR 391 and ZAR 520 per adult equivalent per month, while the REC ranged between ZAR 239 and ZAR 520 per household per month in 2014/2015. The average actual energy expenditure (shown in Table 2) just falls into this interval. Although the REC for South African households is close to average actual energy expenditure, it is far below the modelled energy expenditure for the UK, which is between ZAR 1 947 and ZAR 2 876 per month [10].

Detailed REC estimates from the three methods are shown in Tables 6, 7 and 8 respectively. According to Tables 6 and 7, energy requirements for single households (one adult without child) are the largest in both log-linear expenditure and linear Engel curve methods due to the negative expenditure scale of household size gradient.

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[10]The UK's estimated energy requirements were about GBP 107 to GBP 158 per month in 2009 (Hills, 2011). We convert the values to South African Rand by using exchange rate 1 GBP ≈ 13 ZAR in 2009, and then inflate the ZAR value by 1.4, such that the UK's estimation is comparable with the South Africa's in the year of 2015.

Table 5: Estimates of required and subsistence energy expenditure (unit: ZAR)

	Log-linear expenditure model	Linear Engel curve	Semiparametric Engel curve
Min REC	340.34	238.81	252.91
Max REC	391.34	519.58	462.45
Median REC	367.92	356.84	389.09
Mean REC	368.48	390.31	375.09
Subsistence energy expenditure	391.34	519.58	408.70

REC (required energy consumption) is calculated from equation (3), and subsistence energy expenditure is from equation (2). Mean and median REC are calculated as per household per month values, and subsistence energy expenditure is in per adult equivalent per month.

Table 6: Required energy expenditure by log-linear expenditure model (unit: ZAR)

Household size	Required energy expenditure
1	391.34
2	376.39
3	367.92
4	362.02
5	357.50
6	353.86
7	350.81
8	348.19
9	345.89
10	343.85
11	342.01
12	340.34

Table 7: Required energy expenditure by linear Engel curve (unit: ZAR)

	Number of children					
Number of adults	0	1	2	3	4	5
1	519.58	347.72	295.28	268.22	251.02	238.81
2	461.93	356.84	309.14	281.22	262.52	248.92
3	431.22	356.31	315.05	288.59	269.96	256.00
4	410.68	352.95	317.24	292.78	274.84	261.03
5	395.42	348.74	317.53	295.06	278.04	264.63
6	383.37	344.37	316.77	296.15	280.09	267.19
7	373.47	340.08	315.44	296.46	281.35	269.00

Figure 2 portrays the relationship between required and actual energy expenditure by income groups. As shown in the figure, the mean REC is around ZAR 400 across ten income deciles and it does not change much with increased income. While average actual energy expenditure rises with the increase in income. Therefore, the ratio of the actual to required energy expenditure rises. Meanwhile, the grey bars with similar height show that the equivalence scale has limited effect on REC, although REC changes with the equivalence scale estimation method. To be specific, the REC from the log-linear expenditure method is the lowest, while the one from the linear Engel curve has the highest

Table 8: Required energy expenditure by semiparametric Engel curve (unit: ZAR)

Number of adults	Number of children					
	0	1	2	3	4	5
1	408.70	385.20	314.66	345.76	358.92	404.33
2	389.29	366.73	403.35	345.93	262.39	335.95
3	346.70	368.98	294.84	323.82	400.65	261.77
4	378.62	389.09	397.30	252.91	391.66	396.44
5	425.17	429.43	377.76	364.16	372.70	320.67
6	295.25	425.95	357.98	364.40	345.56	385.41
7	411.48	427.01	366.89	382.10	462.45	345.80

value. More importantly, Figure 2 shows that REC is well above actual energy expenditure for low- and mid-income groups (income deciles 1-7), while it is less than actual for higher income groups (income deciles 8-10). On average, the poorest 30% of households consume only around half of their required energy, while the extent of the difference falls as household incomes rise. For the households in the top of the income distribution, they consume more than double their energy requirements. For that reason above, our REC estimates are different from the results produced by the BREDEM model in the UK; see Hills (2011) and Herrero (2017).

4.3. Discussion

To determine what the estimated energy requirement means for a typical South African household, we consider a two-adult and two-child household in an example. The maximum and minimum estimated required energy expenditure for this group are ZAR 309.14 and ZAR 403.35, respectively. Given that annual average Eskom residential electricity price in 2014/2015 is 0.9806 ZAR/kWh (DoE, 2017) [11], these values equate to approximately 315.3 kWh to 411.3 kWh electricity consumption per household per month. The estimated REC is supposed to meet household basic energy needs for lighting, cooking, heating, cooling and entertainment (Welsch and Biermann, 2017; Charlier and Legendre, 2019). To have an in-depth understanding of the estimated REC, we conduct a further analysis on daily energy usage for home appliances. As shown in Table 9, each appliance's electricity consumption is the multiplication of its rated power and duration of usage. South Africa has a mild climate, hence water heating by electric geysers instead of space heating is the largest user of electricity in domestic sector. Meyer (2000) argues that water heating consumes about 40% to 50% of monthly electricity for an average middle-to-upper income household [12]. In our case, electricity use in water heating is assigned to be 19% for the minimum electricity consumption scenario and 29% for the maximum electricity consumption scenario.

Although the energy consumption patterns presented in Table 9 represent only one typical realisation out of various potential energy consumption patterns, it allows us to describe how the estimated minimum and maximum REC could

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[11]Note that this price is only applicable to Eskom's direct sales to the residential consumers. Normally the distribution tariff by local authorities is higher than Eskom's.

[12]Further, a recent report from Department of Energy of South Africa shows that water heating accounts for 39% of household electricity use, see https://www.savingenergy.org.za/wp-content/uploads/2018/05/Energy-Label-Learner-Guide.pdf.

Figure 2: Required versus actual energy expenditure by income groups Note: Only one of the ratio lines is presented in this figure, because the ratios from three methods are so close to each other such that the lines are overlapped.
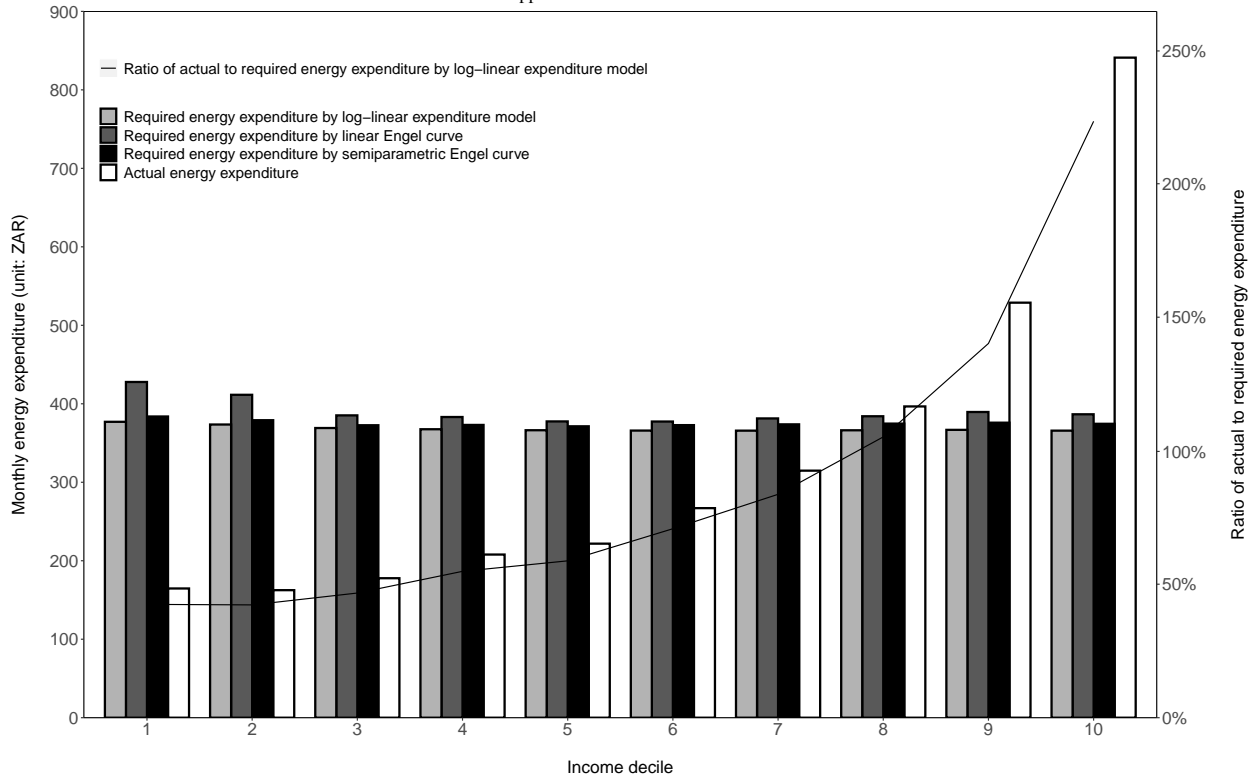
be utilised by family members for their basic energy needs.

5. Conclusions

This paper has developed an equivalence scale approach to model required energy consumption at the household level. Data from a recent South African household expenditure survey have been investigated as a case study. We found that: (i) the energy equivalence scale is different from income equivalence scales and energy equivalence factors applied in developed country studies; (ii) the choice of equivalence estimation method has little impact on REC; (iii) on average, the estimates of required energy consumption are well above actual energy expenditure for low- and mid-income groups, while they are less than actual for high-income groups. The results are consistent with an expectation that the basic energy needs of most poor households in South Africa have not been met, due to the poverty in the country.

Our study is the first one in literature to estimate required energy consumption based on equivalence scale methods applied to widely available household expenditure survey data. While common energy poverty indicators use actual energy expenditure instead of required energy expenditure, the modelling of required energy consumption has largely been unaddressed. Our study contributes to this issue by developing an equivalence scale based approach to model

Table 9: Monthly electricity consumption of household appliances in South Africa

Electrical appliance	Rated power (kW)	Scenario 1: Minimum REC		Scenario 2: Maximum REC	
		Duration (hours/day)	Power consumption (kWh/day)	Duration (hours/day)	Power consumption (kWh/day)
Lamp bulb	0.06	5.00	0.30	5.00	0.30
Electric stove	2.20	1.00	2.20	1.00	2.20
Microwave oven	1.00	0.50	0.50	0.50	0.50
Kettle	1.20	0.50	0.60	0.50	0.60
Refrigerator	0.40	4.50	1.80	6.00	2.40
Electrical water heater (geyser)	2.00	1.00	2.00	2.00	4.00
Washing machine	1.00	2.00	2.00	2.00	2.00
Iron	1.20	0.50	0.60	1.00	1.20
Television	0.15	3.00	0.45	3.00	0.45
Charger - for cellphones	0.01	6.00	0.06	6.00	0.06
Total (kWh/day)			10.51		13.71
Total (kWh/month)			315.3		411.3

Note: Total kWh/month is calculated as total daily kWh (kilowatt hour) multiplied by 30 days. Source: Rated power of appliance is from Setlhaolo et al. (2014) and Setlhaolo and Xia (2015).

required energy consumption. Our method can be applied in a variety of settings in which necessary household energy usage information is not available. In addition, the methods for energy equivalence scale estimation help to adjust energy consumption to account for different household size and demographic profiles.

One specific limitation in our analysis is that we regard household size and structure and household expenditure as the main determinants of household basic energy need without including more energy related factors. This limitation could be addressed in the future work, by examining additional relevant characteristics, such as other socio-demographic, geographic or physical characteristics.

A more general limitation of this study is that we were not able to estimate household energy requirements based on domestic electrical appliance and other fuel usage information. The household expenditure survey captured ownership of selected household appliances, though detailed information like the number and power of each appliance is not available. Hence, further assumptions would be needed, although a deeper survey would offer a useful solution. Additional data would also allow for a comparison between our proposed method and the one underpinned by detailed energy usage information based on engineering method.

Appendix A. Additional Tables and Results

Table A1 presents actual energy expenditure by family types. Tables A2 and A3 report regression results by the log-linear expenditure and linear Engel curve methods, respectively.

Table A1: Actual energy expenditure by family types (unit: ZAR)

Number of adults	Number of children					
	0	1	2	3	4	5
1	231.16	207.07	215.28	179.44	155.96	128.53
2	350.61	298.90	354.85	294.71	237.54	212.26
3	426.21	343.44	317.01	257.72	252.81	220.46
4	491.61	365.98	310.74	247.66	252.94	182.08
5	431.77	362.52	340.80	319.42	250.26	243.68
6	385.34	334.60	362.57	279.42	269.58	220.30
7	450.52	388.51	252.73	235.06	276.44	273.85

Average energy expenditure per month by family types.

Table A2: Estimates by log-linear expenditure model

	Estimate	Standard error	t value	Pr($> |t|$)
Intercept	0.85	(0.039)	21.92	0.00
Log household size	-0.06	(0.007)	-7.75	0.00
Log household expenditure	0.55	(0.005)	115.37	0.00

Regression results from the log-linear expenditure model are estimated based on equation (4).

Table A3: Estimates by linear Engel curve

	Estimate	Standard error	t value	Pr($> |t|$)
Intercept	0.30	(0.003)	95.69	0.00
Log expenditure per household member	-0.03	(0.000)	-70.69	0.00
Log household size	-0.03	(0.001)	-41.57	0.00
Children as proportion in household	-0.02	(0.002)	-7.10	0.00

Regression results by the linear Engel curve are estimated based on equation (6).

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