FACILITATING SOLAR-BASED RURAL ELECTRIFICATION PROJECTS IN SOUTH AFRICA BY APPLYING A BOTTOM-UP ENERGY DEMAND MODELLING APPROACH

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Abstract

Renewable-powered projects such as mini-grids and solar home systems (SHS) are often considered as solutions for rural electrification in the cases where grid-expansion becomes unaffordable and inefficient. However, to reach an optimal system design, project developers need to have an accurate estimation of the electricity demand. Estimating it is a challenging task due to its resource-consuming nature and the uncertainties from existing models led by the lack of data from these areas. This paper provides a methodology to estimate the rural electricity demand at a household (HH) scale in the South African context. The method is based on a statistical approach taking demographic and socioeconomic evidences from +6,000 rural HH for the years 2015-2016. It utilizes a bottom-up appliances ownership model and human behaviour patterns to give as result the daily electricity consumption per HH, the typical load profiles at a 30min resolution, and geo-spaced projections by province. It was found that the average electricity demand to meet a HH's basic requirements (lighting, charging mobile phones, and using radios) is 0.59 kWh/day (215.35 kWh/year). Two case studies are applied to Limpopo and KwaZulu-Natal provinces, for which it was found that the calculated demand could be met up to 52.5% by a SHS.

Keywords: Bottom-up energy modelling; energy demand; Geographic Information System; load profiles; rural electrification; solar home systems.

1. Introduction

Previous studies have found that there is a close link between electricity access and socioeconomic development [1]; thus, electrification projects are often listed as a top priority in developing countries. Still, in Africa, electricity is inaccessible, unaffordable and unreliable for most people [2]. More than 95% of the share of global population without electricity access lies in sub-Saharan Africa, a region rich in energy resources, but very poor in energy supply [3]. Multiple efforts have been taken by African governments for giving electricity access to remote rural areas, however, these have had little or no success at all.

The installation of Solar Home System (SHS) have been considered as the foremost solution taken in rural electrification projects in developing countries due to its apparent cost-effectiveness [4]. Nevertheless, evidences such as the SHS Program applied in Bangladesh, have revealed that SHS does not necessarily enhance the development of rural areas [5]. South Africa was one of the pioneers on implementing in the early 1990's an Integrated National Electrification Program (INEP), which first phase focused on the extension of the national grid developed by Eskom (the main national utility company) [6]. However, after realising that this program was not benefitting remote rural dwellers, the SHS was added to the INEP in 2002 as an alternative solution [7]. Since its inception, the latter has been facing several technical and economic challenges, being one of them the inability of the designed SHS on meeting the electricity demand of rural households (HH) [8].

This paper aims at supporting national authorities and project developers on designing optimal solar-based electrification solutions by providing a methodology to estimate the electricity demand of rural households in South Africa. It starts with the application of regression models to compute the electrical appliances ownership (considering mobile phones, radios, televisions, refrigerators, microwaves, stoves and computers) at a HH scale, depending on different demographic and socioeconomic conditions. The time of use (TOU) of the appliances and lighting purposes is then calculated performing a human behaviour probabilistic analysis. Considering power rates provided by previous on-site studies, the electricity demand per HH per day is calculated. Typical load profiles with a 30min resolution are also simulated by province to identify the peak power and the time of the day it tends to occur. The results are presented in geo-spaced projections using Geographic Information System (GIS) tools, and finally, a discussion regarding the capacity of the current SHS South African program to meet the calculated electricity demand is presented by applying two case studies analysed for the provinces of Limpopo and KwaZulu-Natal.

2. Data management

When analysing rural areas, the main challenge is the lack of reliable data. Being South Africa one of the most developed countries in sub-Saharan Africa, it has solid open-data platforms held by the National Bureau of Statistics (STATS SA), which are meant to support policymakers. To build the appliances ownership models in this study, datasets from the General Household Surveys (GHS) of 2015 and 2016 [9] were collected obtaining a total of 6,320 samples. These were randomly divided in a training (70% of the total amount of samples) and testing set (representing the remaining 30%). For the TOU and schedule modelling, the latest Time Use Survey (TUS) [10] – covering the year 2010 was used, containing 7,711 samples. This survey presents detailed information about how South Africans spend their time. To develop the case studies, technical data from the SHS program implemented in Thlatlaganya village (province of Limpopo) was used [11]. The distribution of samples per province is found in Fig. 1.

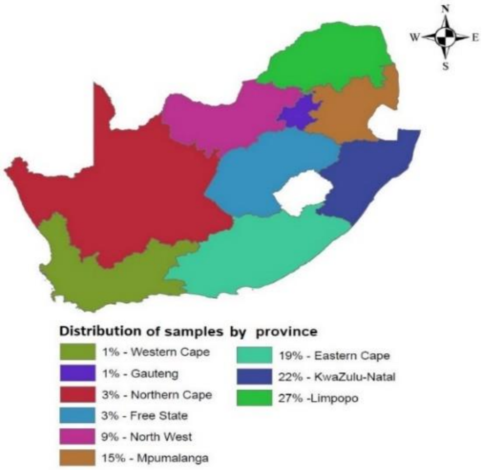


Fig. 1. Samples distribution.

3. Methodology

3.1. Electricity demand modelling

To calculate the daily electricity demand of a South African rural HH, the equation (1) was employed.

$$E = \sum (SR_i * TOU_i * P_i), \qquad kWh/HH/day \qquad (1)$$

Where E is the electricity demand, i the type of appliance, SR the saturation rate, TOU the time of use, and P the power rate. In this study, three categories considering the appliances ownership level of the HH are proposed as “Basic”. “Basic + TV” and “Total” ownership. These are detailed in Table 1.

Appliances ownership level	Supported energy uses
Basic	Lighting, mobile phones’ charging, and radios.
Basic + TV	Basic level and TV
Total	Basic + TV level and refrigerators, microwaves, stoves and computers

Table 1. Categories of appliances ownership.

3.1.1. Appliances ownership

Multivariate regression methods were selected to model each electrical appliance’s ownership using linear and non-linear relationships. The general form of a multivariate linear regression method is given by (2).

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon \qquad (2)$$

Where y is the dependent variable (appliances saturation rate), β_0 the intercept, $\beta_{1\ldots n}$ the regression coefficients, $x_{1\ldots n}$ represent the independent variables, and ε is the error term. Logarithmic transformations were applied in some of the models in order to obtain a better fit.

3.1.1.1. Selected variables

Different variables at a HH scale were tested in order to find the most suitable to each analysed appliance’s model. These were selected based on their significance to the models using the Student’s t-test described by (3). This test measures the size of the difference in the means of two populations, relative to the variation in the sample data – represented in units of standard error, with the increase of the t-value, the significance that the analysed variable adds to the model increases as well [12].

$$t - value = \frac{\beta - \beta_0}{SE_\beta} \qquad (3)$$

Where β is the least square estimator (regression coefficient), β_0 is the intercept, and SE_β is the standard error of the least square estimator. The final selected variables for the models are presented in Table 2. Some of the variables showed collinearity, but it was neglected due to its insignificant value (Pearson coefficient lower than 0.6).

Variable	Description	Unit
Size	Number of people in HH	People
Sex	Sex of the HH head	0 – 1[1]
Age	Age of the HH head	Years
Marital status	HH head is currently or has been married	0 – 1[2]
Population group	HH head belongs to the white population group	0 – 1[2]
Health status	HH head has health problems	0 – 1[2]
Literacy	HH head can read/write in at least one language	0 – 1[2]
Employment status	HH head has a salaried employment	0 – 1[2]
Income	HH total monthly income	Rands
Rooms	Number of rooms in HH	Units
Dwelling type	Dwelling is built in traditional materials*	0 – 1[2]
Grid connection	HH is connected to the electricity grid	0 – 1[2]

*[1]one indicating male, zero otherwise. [2]one indicating a positive answer, zero otherwise. *materials found locally, excl. brick/concrete/block.*

Table 2. Selected independent variables.

3.1.2. Lightbulbs

The amount of lightbulbs owned by rural HH was calculated based on the assumption found in [13], which states that each HH will have one lightbulb per room. The variable containing the number of rooms per HH was found in the GHS.

3.1.3. Time of Use (TOU)

The TUS dataset contains detailed information regarding the time allocation of South African rural HH. Among other questions, two people per HH were asked to complete a diary with predetermined activities that they needed to fill at every 30min for 24hrs. This diary also allowed people to describe if they perform simultaneous activities and to specify the location of these. According to [14], the TOU for each appliance can be calculated based on daily frequency curves of use related to each domestic activity; therefore, these curves were computed taking into account the following probabilistic functions:

- *Activity in the HH:* People can only use the electrical appliances if they are in the HH and in an awake state.
- *Simultaneity:* People can make use of multiple electrical appliances at the same time. Therefore, some appliances will have a main and secondary use per activity.

The results of the probability function of *activity in the HH* are found in Fig. 2. The domestic activities considered in this study are presented in Table 3, along with their link to each of the analysed appliances including their main and simultaneous use. In the case of the mobile phones, only the charging hours were considered in the analysis, while the refrigerators works with a load cycle and it's not related to any studied activity, both TOU were taken from [15]. Following the same reference, the lighting hours were considered from 17:00 to 00:00. The calculated TOU are presented in Table 4.

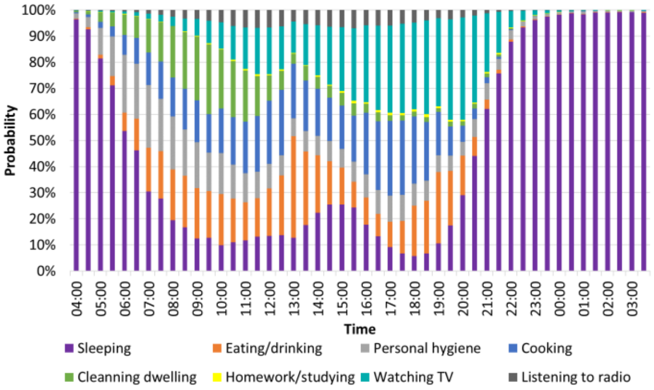


Fig. 2. Activity in the HH.

	Activities		Related Appliances				
Code	Main	Simultaneous (Code)	Radio	TV	Computer	Stove	Microwave
1	Sleeping	-	-	-	-	-	-
2	Eating/drinking	7,8	O	O	-	-	-
3	Personal hygiene	-	-	-	-	-	-
4	Cooking	2,7,8	O	O	-	X	X
5	Cleaning dwelling	8	O	-	-	-	-
6	Homework/studiyng	-	-	-	X	-	-
7	Watching TV	-	-	X	-	-	-
8	Listening to radio	-	X	-	-	-	-

Where "X" represents the main activity, "O" the secondary use, and "–"not applicable.

Table 3. Relationship between activities and appliances.

Activity Type	TOU (hrs/day)							
	Radio	TV	Computer	Stove	Microwave	Fridge	M. Phone	Lighting
Main	4.5	3.5	1	2.5	0.25	5	3	4.5
Secondary	4.5	4.5	-	-	-	-	-	-

Table 4. Calculated TOU.

3.1.4. Power rates

The power rates used for this study were taken from previous on-site studies from the Hluleka and Lucingweni pilot mini-grid projects in South Africa presented in [16]; these are found in Table 5.

Power rate (W)							
Radio	**TV**	**Computer**	**Stove**	**Microwave**	**Fridge**	**M. Phone**	**Lightbulbs**
10	70	150	700	600	100	10	15

Table 5. Power rates.

3.2. Load profiles modelling

A typical schedule was created from the TUS dataset based on the probabilistic analysis showed in section 3.1.3. Then, a typical load profile for a non-grid connected rural HH per province (as well as for the country) was simulated at a 30min resolution, considering the results obtained from the appliances ownership modelling and the power rates from the Table 5.

4. Results and discussion

4.1. Appliances ownership models

In this section, the parameters and testing results of each appliance's model are presented. Fig. 3 shows the error distribution of the models when these were applied to the testing dataset. In this figure, the accuracy of the models can be observed by having a value of 4.5% as the highest standard error (corresponding to the mobile phone's model).

4.1.1. Radio

Due to its low price and electricity consumption, radios are widely owned by rural HH [13]. Its model is given by (4), and obtained an R^2 of 0.63.

$$\textbf{Radio ownership} = 0.39 + 0.05\,(\text{Sex}) + 0.02\,(\text{Rooms}) + 0.15\,(\text{Marital status}) - 0.10\,(\text{Health}) + 0.27\,(\text{Literacy}) + 0.12\,(\text{Employment status}) \tag{4}$$

4.1.2. Mobile phone

Evidence has shown that the ownership of this electronic device has increased dramatically in developing countries over the years. This model obtained an R^2 of 0.70, and the resulting equation is given by (5):

$$\mathbf{ln(\text{Mobile phone ownership})} = -1.1 + 0.54\ln(\text{Size}) + 0.08\,(\text{Sex}) + 0.15\ln(\text{Age}) - 0.09\,(\text{Dwelling type}) + 0.11\,(\text{Employment status}) + 0.07\ln(\text{Income}) \tag{5}$$

4.1.3. Television

Previous studies have demonstrated that televisions are by far the most desirable electrical use after lighting [15]. Equation (6) describes the final model.

$$\textbf{TV ownership} = 0.07 - 0.1(\text{Dwelling type}) + 0.21\,(\text{Grid connection}) + 0.15\ln(\text{Rooms}) + 0.04\ln(\text{Income}) + 0.04\,(\text{Marital Status}) \tag{6}$$

Obtaining an R^2 of 0.71, the model shows that a HH will have access to one or more TVs if the dwelling is not made of traditional materials, has grid connection, has more rooms and income, and if the head of the HH is currently or has been married before.

4.1.4. Computer

The ownership of computers is continuously expanding in developing countries [18], but still its ownership among rural HH in South Africa is very low. Its model is given by (7):

$$\textbf{Computer ownership} = 0.04 + 0.35\,(\text{Population group}) - 0.002\,(\text{Age}) - 0.04\,(\text{Dwelling type}) + 0.012\,(\text{Rooms}) + 0.000015\,(\text{Income}) \tag{7}$$

Obtaining an R^2 of 0.52. The model shows an interesting positive relationship between the population group of the HH head and his age with the ownership of this device; the HH tends to own a computer if the HH head is white and young.

4.1.5. Refrigerator

This appliance is considered as highly wanted but relatively expensive for rural HH [17]. Its model is given by (8), obtaining an R^2 of 0.61. Because of its load-cycle operation, it shows a great dependence on the grid connection of the HH.

$$\textbf{Refrigerator ownership} = -0.37 - 0.03\,(\text{Sex}) - 0.11\,(\text{Dwelling type}) + 0.23\,(\text{Grid connection}) + 0.14\ln(\text{Rooms}) + 0.08\,(\text{Employment status}) + 0.09\ln(\text{Income}) \tag{8}$$

4.1.6. Stove

The model for this appliance is given by (9):

$$\textbf{Stove ownership} = 0.57 - 0.06\,(\text{Dwelling type}) + 0.008\,(\text{Rooms}) + 0.24\,(\text{Grid connection}) + 0.000005(\text{Income}) - 0.07\,(\text{Health}) \tag{9}$$

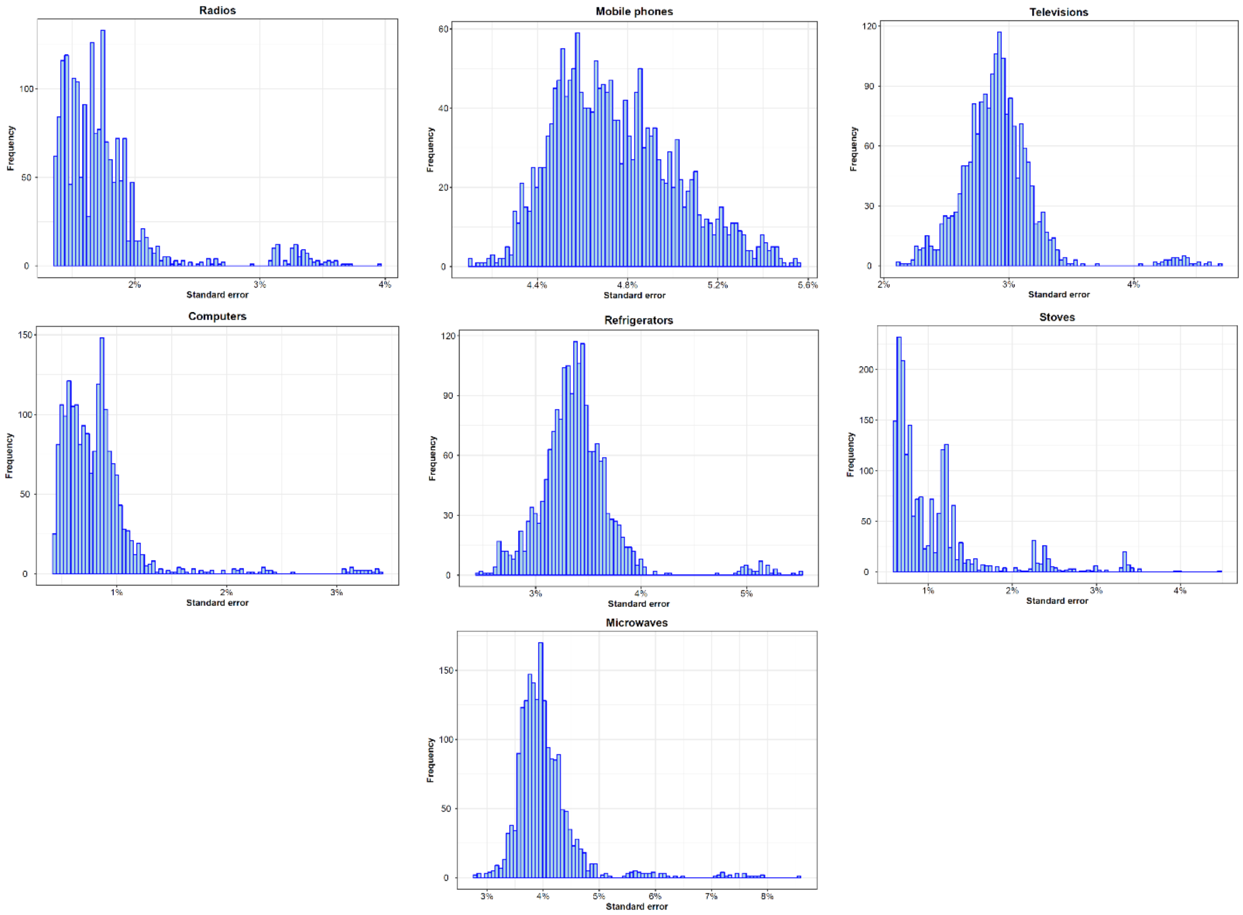
Obtaining an R^2 of 0.54. The relationship between the health of the HH head and the use of an electric stove is clearly revealed. Cooking is the primary energy use of a rural HH, and about 2.7 billion people worldwide still rely on biomass as fuel for this purpose [3]. The use of biomass brings health problems (mainly respiratory) to HH members due to its inefficient combustion [2], which can be avoid if the HH has electricity access.

4.1.7. Microwave

This appliance, along with the electric stove is highly electricity consuming, therefore it is not popular among rural HH. Obtaining an R^2 of 0.52, its ownership is described by (10):

$$\textbf{Microwave ownership} = -0.77 + 0.24\,(\text{Population group}) - 0.09\,(\text{Dwelling type}) + 0.12\,(\text{Grid connection}) + 0.18\ln(\text{Rooms}) + 0.08\,(\text{Employment status}) + 0.09\ln(\text{Income}) \tag{10}$$

As well as for computers, it shows a high correlation with the population group of the HH head, and if the HH is connected to the electricity grid.


Radios

Mobile phones

Televisions

Computers

Refrigerators

Stoves

Microwaves

Fig. 3. Error distribution of appliances ownership models.

4.2. Electricity demand modelling

As explained in section 3.1, three categories are proposed to calculate the current electricity demand of South African rural HH. It was found that the average requirements to meet the basic needs of a rural HH (lighting, charging mobile phones, and using radios) in the country is 0.59 kWh/day (215.35 kWh/year). The results for each category per province are presented in Fig. 4. For the basic electricity demand level, the province with the lowest value is Free State with an average of 0.52 kWh/day for presenting the lowest lighting demand – which is related to the number of rooms per HH (having the lowest average with 5.25). While Gauteng presents the highest value with 0.63 kWh/day, related to having the highest mobile phone ownership (2.93/HH) and one of the highest lighting consumption (with an average of 6.66 rooms/HH). Comparing the results obtained for the province of Limpopo with the average load pattern for the SHS project at Thlatlaganya village (Limpopo), which was identified as 0.54 kWh/HH/day in 2011 [11], a difference of 10% is found, while comparing it with the country's average the difference is of 7%. Gauteng has the highest TV ownership (97%), which is proven by presenting the highest electricity demand in the "Basic + TV" category (1.13 kWh/day), while in this case, Eastern Cape shows the lowest demand with 0.97 kWh/day, with a TV ownership of 83%. Considering the "Total" access category, Gauteng and Western Cape (the two wealthiest provinces) presented the highest electricity consumption values with an average of 3.42 and 3.41 kWh/day respectively. While Limpopo has the lowest with 2.99 kWh/day.

In Fig. 5, it is interesting to see that not necessarily the province with the highest rural electricity demand ("Total" category) has the highest percentage of grid-connected rural HH (as in the case of Western Cape). According to the survey's results, most of rural HH without electricity access use diesel generators to power their devices. In Fig. 6, the rural population distribution is presented together with the "Basic" and "Total" categories. Here it can be noticed that the highest "Basic" electricity demand lies where higher concentrations of rural HH are located. Comparing this result with the one for the "Total" category, it shows that rural population is more likely to have low power-consuming devices rather than big and expensive appliances, such as televisions, computers, refrigerators, stoves and microwaves.

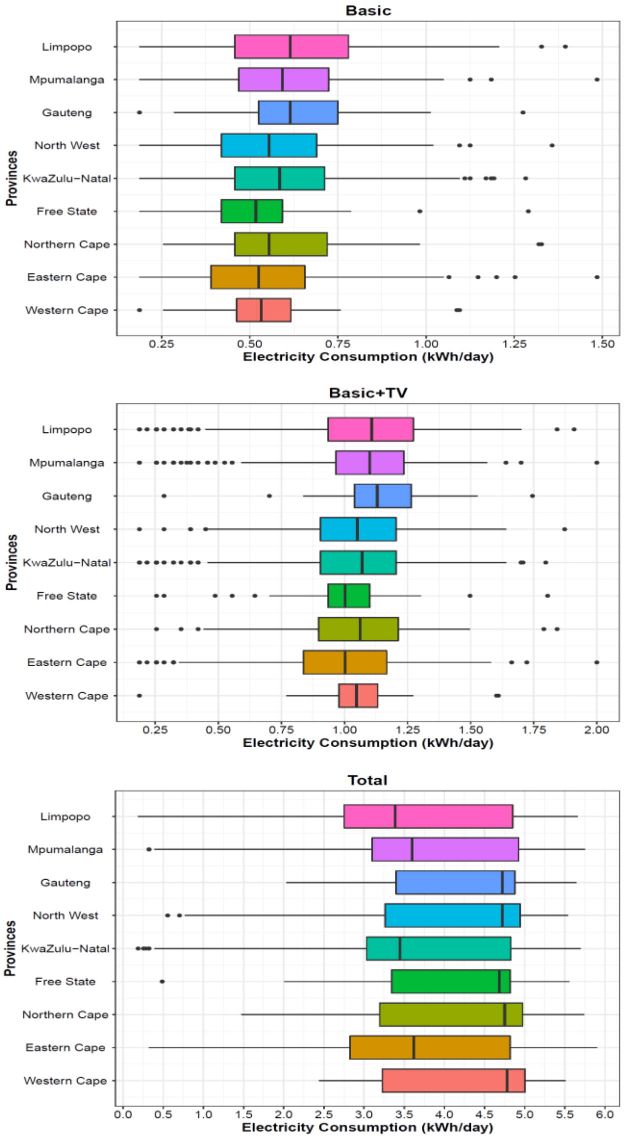


Fig. 4. Electricity demand categories per province.

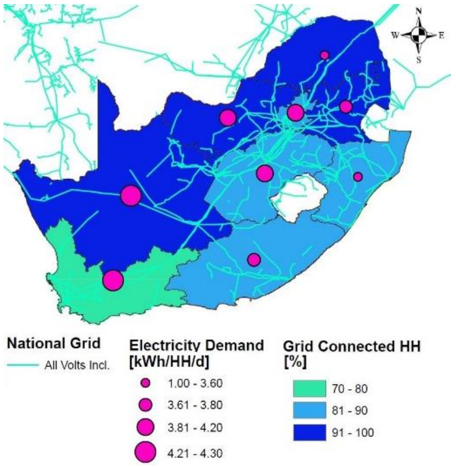


Fig. 5. Rural electricity demand ("Total" category) and rural grid connection.

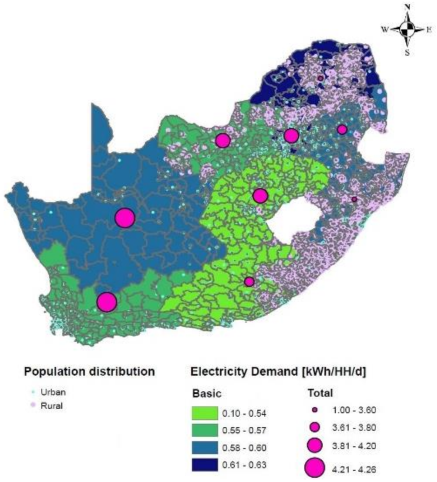


Fig. 6. Rural electricity demand (Basic and Total) and population distribution.

4.3. Load Profiles

The load profile per province were simulated at a 30min resolution for a typical non-grid connected rural HH. The results (found in Fig. 7) show that the average peak power has a value of 377 W and occurs at around 18:00. At this time of the day, there are more probabilities of activity in the HH (see Fig. 2 as reference) because all the HH members are at home (coming back from work and school). Besides this, other two peaks are identified at 08:00 and 12:00, which are related to the meal hours (involving entertainment and socializing activities).

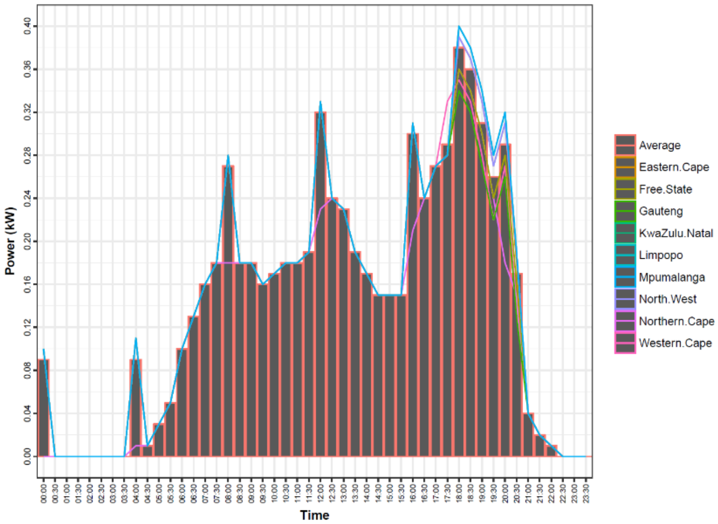


Fig. 7. Load profiles of a typical non-grid connected rural HH by province, and national average.

4.4. Can these demands be met by a SHS?

Taking as reference the standard SHS system that was implemented in Thlatlaganya village (province of Limpopo); two case studies were simulated in RETScreen^{TM}[19] to find the capacity factor and percentage of load that is covered by the SHS through the year. The system consists of a 75 WP solar panel, a charge controller, and a 100Ah, 12 V battery system with 4 days of autonomy [11]; The installation of a SHS in a rural HH in the province of Limpopo (near Thlatlaganya village) and one in KwaZulu-Natal (near the city of Durban) were considered. The slopes of the panels were fixed at the value of the latitude of each location. The weather conditions were taken from the meteorological stations located in Pietersburg (SAAF) Lat: -23.9°N, Long: 29.5°E; and Durban/Louis Botha Lat: -30°N, Long: 31°E, the solar radiation details are found in Table 6.

	Thlatlaganya (Limpopo)		**Durban (KwaZulu-Natal)**	
	Daily solar radiation - horizontal	**Daily solar radiation - tilted**	**Daily solar radiation - horizontal**	**Daily solar radiation - tilted**
Month	**kWh/m²/d**	**kWh/m²/d**	**kWh/m²/d**	**kWh/m²/d**
January	7.52	6.55	5.57	5.09
February	6.56	6.16	5.46	5.29
March	6.09	6.26	4.92	5.19
April	5.35	6.22	3.98	4.71
May	4.79	6.31	3.31	4.46
June	4.35	6.11	3.04	4.44
July	4.15	5.55	3.20	4.52
August	5.05	6.19	3.73	4.61
September	5.62	6.03	4.06	4.41
October	6.58	6.35	4.76	4.71
November	7.22	6.42	5.12	4.75
December	6.86	5.91	5.81	5.22
Annual	**5.84**	**6.17**	**4.41**	**4.78**

Table 6. Solar radiation details of two case studies.

The standard SHS was tested with the three electricity demand categories. In Table 7, the results show that for these case studies, the standard SHS can support up to 52.5% of the “Basic” electricity demand category of a rural HH located in Lompopo, and up to 43.6% of one located in KwaZulu-Natal, while the fraction that can meet the “Total” category is very small.

Parameters	**Thlatlaganya (Limpopo)**			**Durban (KwaZulu-Natal)**		
	Basic	Basic + TV	Total	Basic	Basic + TV	Total
Electricity demand (MWh/year)	0.23	0.39	1.09	0.22	0.38	1.12
SHS electricity delivered to load (MWh/year)	0.12			0.09		
Solar fraction (%)	52.50	33.10	10.00	43.60	25.70	7.00
Capacity factor (%)	24.40			19.00		

Table 7. SHS simulation results.

In Fig. 8, the solar potential is mapped against the population distribution and the “Basic” category of electricity demand. It can be observed that rural population is mostly concentrated in the regions with less solar potential, and their “Basic” electricity demand is high. In the provinces of North West, Free State and Eastern Cape, where the solar potential is high and the basic electricity requirements for a rural HH is low, the implementation of the SHS could be more technically efficient.

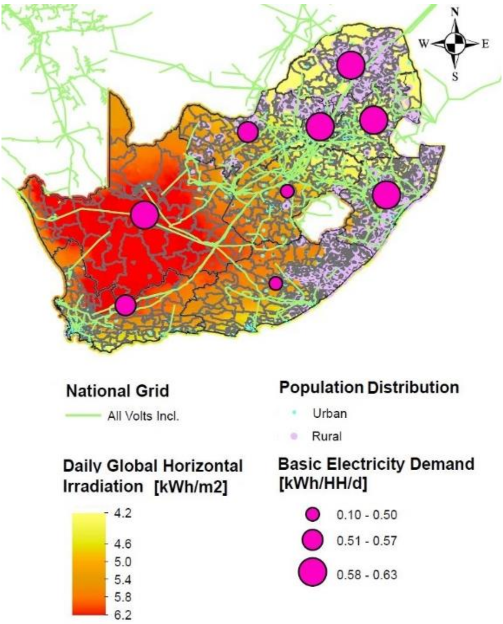


Fig. 8. Solar potential, population distribution and basic electricity demand.

5. Conclusion

The methodology presented in this paper gives a foundation for modelling the electricity demand of rural households in South Africa, considering demographic and socioeconomic aspects, together with human behaviour patterns as a potential solution to improve the design of solar-based rural electrification projects. Until now, a small amount of studies have focused on modelling the electricity demand in South Africa, such as [20], in which a top-down modelling technique for urban residential consumers was presented. However, none of them focused on modelling de demand of rural HH using a bottom-up appliances and human behaviour modelling approach. On the other hand, many researchers have focused on assessing the effectiveness of the SHS program implemented in the country since 2002, and they rely on demand estimations and measurements that have been applied in previous electrification projects, which contains a high amount of uncertainties due to the constantly changing socioeconomic environment that characterises rural areas. In this study, the application of SHS was tested in two locations; however, the results show that the system can partially (but not completely) meet the demand of these HH. As mentioned in section 4.4, in provinces such as North West, Free State and Eastern Cape, these systems can be technically more efficient to meet the basic requirements of rural HH. However, the system does not entirely meet the load coming from productive activities that could support the socioeconomic development of these areas; therefore, more sustainable solutions such as the implementation of mini-grids should be explored.

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