Energy (in)justice in off-grid rural electrification policy: South Africa in focus

Abstract

Generally speaking, increasing rural marginalisation in sub-Saharan Africa has sat alongside a rise in energy poor homes in rural off-grid communities. Even measures meant to improve electricity access have exacerbated the energy access gap between grid connected and off-grid homes. For example, the South African Non-Grid Electrification Policy Guidelines for electrifying off-grid, rural poor homes promote the adoption of Solar Home Systems (SHS), which are expected to produce 7.5 kWh/month on average. However, for poor homes within grid coverage, the Free Basic Electricity (FBE) programme allocates 50 kWh/month. This paper investigates the resulting disparity in terms of electricity cost (ZAR/kWh), including associated costs for heating, cooking and other needs. It does so through the energy justice framework, highlighting the mismatch in policy formulation (procedural injustice), resource distribution (distributive injustice) and spatial distribution (injustice in the recognition of population groups' special needs). Through a combination of mathematics and social science perspectives, it then moves beyond a critique of the current SHS system to proposes a new one: a hybrid generation approach with a flexible pricing scheme and centralized system of operation that is both ethically compliant *and* capable of improving electricity access to off-grid communities with standards comparable to grid access.

Keywords - energy justice; policy implementation; hybrid electricity generation; South Africa

Contents

Introduction

As of 2014, sub-Sahara Africa (SSA) had 62.8% of its population living in rural areas, of which only 35.3% had access to electricity. In comparison, urban areas had a 71.6% electrification rate (Baurzhan and Jenkins 2016). In striving to bridge the widening energy access gap between rural and urban areas, countries in SSA have adopted varied measures. Notable among these has been the use of Solar Home System (SHS)[1], designed with the aim to increase the availability of energy to all. Yet, despite the widespread penetration of SHS in rural communities and the regional variations therein, there has been no noticeable or systematic reduction in

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[1] Which are made up of 1-50 Wp photovoltaic panel, 1 charge controller, wiring and small outlets for small appliances, 1-105 Ah battery and 4 energy efficient compact fluorescent lamps.

rural peripheralisation[2] and poverty alleviation to date. We make this perhaps controversial statement based on the exhaustive findings on the failure of 29 trans-regional renewable energy projects in SSA by Ikejemba et al. 2017, the findings on the failure of SHS projects and in particular the Lucingweni project by Azimoh et al. 2016 and the position of Urmee and Md 2016. Each of these has inadvertently created instances of rural peripheralisation." For South Africa in particular, Azimoh et al. 2016 state that "*despite substantial government spending on SHS, assessment of the socio-economic impact of the South African SHS program revealed that the energy needs of the households are seldom met due to the low power capacity of the system.*" Indeed, according to Baurzhan and Jenkins 2016, 727 million people in SSA continue to rely on traditional biomass and charcoal as their primary cooking fuel.

Urmee and Md 2016 further corroborate this situation as they explain that end-users expectations of SHS and the performance of these SHS did not match, especially in terms of load capacity and hours of utilisation. Most end-users had expected grid quality electricity level from SHS and did not have their expectations fulfilled. This implies, in effect, that the increasingly widespread use of SHS has not improved electricity access per capita (kWh) (which is about 511.90 kWh compared to 3064.50 kWh for the world (average)) (Baurzhan and Jenkins 2016). Thus, the huge costs of installation of these SHS and their limited usage options creates a gap in terms of energy access between grid connected and off-grid households, leading to rural peripheralisation (a somewhat similar example to the case of the smart meter roll out in the UK, perhaps (Sovacool et al. 2017)). Further, this low rate of electricity access (which some may argue is a product of ineffective policy, see Azimoh et al. 2016), increases the exposure of off-grid rural households to diseases such as childhood pneumonia, chronic obstructive pulmonary disease (COPD), and lung cancer caused by the smoke emanating from alternative energy sources like firewood (Baurzhan and Jenkins 2016).

This paper comes to this challenge from two perspectives. Firstly, it seeks to outline that this peripheralisation and maldistribution of electricity access is an issue of energy justice. Secondly, in order to move past what would otherwise just be a critique of off-grid electrification policies, it makes a practically oriented contribution to addressing these failings through mathematics and modelling. Specifically, we address this gap by examining the efficacy of the current SHS system and based on its failings, proposing an alternative hybrid generation system that meets the demands of the energy justice framework. As an impact-oriented output, we provide, in effect, an alternative means of electrifying off-grid communities that incorporates energy justice values and in terms of its modelled impact, is ethically compliant.

This work is as timely as it is necessary for (at least) two reasons. Firstly, despite the claim that energy justice scholarship appears across many disciplines (Jenkins et al. 2016), few mathematics and modelling techniques have been applied. Indeed, this paper is arguably the first of its kind (although we do acknowledge the work of Bednar et al. 2017 which also uses modelling techniques, albeit in a very different way). In this regard, we provide an important applied contribution. Secondly, and practically, according to Mandelli et al. 2016, about 60% of additional electricity generation needed to provide universal access to energy is expected to be generated through off-grid systems. For this reason, we require sustainable generation schemes that are both ethically compliant *and* capable of improving electricity access to off-grid communities with standards comparable to grid access. This paper illustrates one potential means of achieving this. This has implications across SSA countries, developing countries in Asia, and indeed, many regions of the world.

This paper proceeds as follows. We begin with an overview of the energy justice concept followed by the South African case. Then, using modelling techniques, we investigate the potential SHS output power across seven provinces in South Africa using weather data from nine South African weather stations. We illustrate that a lack of consideration for the spatial distribution of the population and the stochasticity of weather conditions negates the benefits of SHS schemes with energy justice knock-ons in terms of procedure (procedural justice) and resource distribution (distributive justice). Our paper also shows that the current electrification plans for off-grid rural poor homes do not guarantee adequate energy access. To remedy this failing, we then present a concerted approach to a viable and sustainable generation platform that hybridizes SHS and diesel-generators. A flexible pricing scheme (for pricing electricity) along with a smart load distribution board Monyei et al. 2016 (that incorporates an artificial intelligence tool (MGA) by Monyei and Adewumi 2017 for dispatching electricity needs) are also presented. As energy justice scholars seek to take their work beyond academic scholarship to practical application (including through engagement with innovative business models (Hiteva and Sovacool 2017, for instance), this is one exciting example of how just electrification processes may be achieved.

1 Energy justice - 5 guiding principles

The concept of energy justice is becoming a much-researched topic that seeks to establish a nexus between energy generation and delivery and justice (equity/fairness) (Jenkins et al. 2016; Sovacool and Dworkin 2015). Islar et al. 2017, p.671 define it as "respecting universal human rights and ensuring that every person has a

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[2] By rural peripheralisation we extend its meaning beyond Sovacool et al. 2017 to mean discrimination in quality and quantity of electricity access to households of the same income bracket due to their proximity to the national grid

right to the level of energy required to attain a minimum of wellbeing". Sovacool and Dworkin 2015 posit that energy justice is capable of assisting the energy decision process and choices of consumers and energy planners by presenting itself as a useful decision-making tool. With this potential in mind, we utilize the energy justice approach to (1) critique the Non Grid Electrification Policy Guidelines, which we argue impedes the development of the off-grid poor rural households, and (2) to argue for our proposed hybrid generation scheme, which can improve off-grid poor rural households quality of life (QoL) and overall welfare whilst achieving energy justice.

Several energy justice frameworks have emerged. The first is the tripartite distributional justice, procedural justice and justice as recognition approach - terms that we have mentioned in passing and continue to apply throughout this piece (see McCauley et al. 2013; Jenkins et al. 2016). The second elaborates on energy justice as an analytical tool that helps in understanding how values can be built into energy systems (Sovacool and Dworkin 2015) and provides the building blocks for a series of core principles later elaborated by Sovacool et al. 2016. Within this paper, we focus on five of the eight principles originally presented[3]:

- The availability principle [Principle 1];
- The affordability principle [Principle 2];
- The due process principle [Principle 3];
- The intra-generational equity principle [Principle 4];
- The sustainability principle [Principle 5]

We also consider an explicitly spatial dimension brought to the fore by Bouzarovski and Simcock 2017 as they conceptualize energy poverty as a form of injustice.

We do not take these approaches to be exclusionary. That is to say, we do not believe that one is better than the other and that they cannot be used in tandem. In our approach, the tripartite energy justice framework offers a means of evaluating energy (in)justices of a spatial nature and principles 1-5 offer a series of goals we should seek to achieve. For this reason, we use these 5 principles alongside the spatial dimension to reflect on the simulation results obtained through our model we present in the proceeding paragraphs.

Before going further, however, and in order to navigate the gap between descriptive and prescriptive claims, the need arises for the formulation of a realistic utopia. For the purposes of this paper, we define a realistic utopia to be an ideal setting in which households are able to meet their monthly billing obligations. With reference to the four major standards of justice theory, Table 1 illustrates the conditions this leaves. This is, in effect, our own normative goal.

Table 1: Conditions of our proposed realistic utopia

Theory	Meaning	Applied approach
Egalitarianism	Favours equality among living entities. Advocates the removal of inequalities among people.	Constrained by the ownership of electrical appliances
Libertarianism	Emphasizes freedom, liberty, voluntary association, and respect of property rights.	Bounded by the maximum hourly allocation allotted to each household
Utilitarianism	The proper course of action is the one that maximises the overall happiness. In other words, actions are right if they are useful or for the benefit of the majority.	Is as measured from the Duration-Comfort plot
Sufficientarianism	Rather than making sure we are equal and all as well of as possible, the aim is to make sure that each of us has enough.	Limited by electrical appliance ownership and hourly demand factor.

2 Electrification in South Africa: An Introduction

With attention to the United Nations (UN) Sustainable Development Goals (SDGs) 7 and 11 (*UN*), and in mitigating the effects of the planned decommissioning of ageing power plants plants 2017, Eskom, a South African electricity public utility, has recently stepped up its construction of additional electricity supply capacity (see *Eskom*). The accelerated efforts by Eskom coincide with the energy crisis that has plagued South Africa since 2008, leading to massive blackouts, load shedding and huge economic losses (today 2015; Kohler 2014). This rapid electrification programme has seen electrification rate move rapidly from less than 33% (in 1990) to 58% (1996) and 90% (2016) and has succeeded largely due to various government policies and interventions (Marquard et al. 2007).

Yet in terms of the socio-economic background of the population, evidence suggests that electrification rates remain deeply uneven between differing ethnic groups, as evidenced by the following tables. Table 2 shows the provincial distribution of South Africa's population by population group for 2015 (an estimated 54,432,000 people in total) (STATSSA 2015). Table 3 then shows the household population distribution across the provinces (calculated using a national average household size of 2.2 (*ArcGIS*)). The number of households connected to the mains across the provinces by population group for 2015 is shown in Table 4. A critical

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[3] Where a full list would include availability, affordability, due process, transparency and accountability, sustainability, equity and responsibility (Sovacool et al. 2016)

evaluation of Table 4 shows that on average across the provinces, household electrification rates for Black African, Coloured households, Indian/Asian population group varies significantly with 54.14% of Black African households electrified compared to 47.87% for Coloured households, 59.29% for Indian/Asian households and 77.40% for White households. This shows a trend for the greater electrification in majority white provinces. Beyond distributional injustice, this is an issue of justice as recognition - the unequal marginalization of a particular group or groups.

According to DME 2009, the majority of the un-electrified households are in deep rural areas necessitating, in their argument, government responsibility for ensuring the electrification of all its citizens, and especially the rural poor in order to improve living conditions. With a similar goal in mind, and to achieve universal access to electricity by 2019, the free basic electricity (FBE) policy was introduced in 2004 to completely subsidize 50 kWh of electricity monthly for the very poor households connected to the grid *GNESD*. This is in line with the 1998 White Paper on energy policy, where emphasis was placed on households access to adequate energy services for cooking, heating, lighting and communication DOE 2012b. In addition, the Non Grid Electrification Policy Guidelines identify non-grid SHS as a suitable temporary alternative to grid electricity for rural, poor and off-grid homes. In order to extend this electricity access, energy service companies (ESCO), concessionaires and service providers act on behalf of the Department of Energy (DOE) to roll out SHS delivery DME 2009.

According to DME 2009, the SHS should produce about 250Wh daily and power a black and white television (for 4 hours), lighting (4 hours), portable radio (10 hours) and phone charging points daily. The implication of this is that on average each off-grid rural poor home gets 7.5 kWh monthly from the SHS. Yet a critical evaluation of the fall-out of this policy reveals the following potential problems:

1. The over-simplification of the policy implementation has failed to consider the varying weather disparity (solar irradiance and temperature) across South Africa, which would affect the output power of the SHS.
2. The failure of the policy to compensate for varying weather conditions across South Africa's provinces creates injustice in resource distribution (distributive injustice) and policy conceptualization.
3. The huge disparity between the FBE allocation of 50 kWh monthly and the estimated 7.5 kWh monthly for on-grid and off-grid poor homes inadvertently contributes to widening energy access gap and increasing energy (electricity) poverty across households. This goes against energy justice in terms of recognition principles since majority of the off-grid poor homes are Black Africans.
4. The full subsidy in form of FBE for on-grid poor homes and 80% subsidy for off-grid poor homes implies that off-grid poor homes on average pay exorbitantly high and varying prices for electricity. This is due to the stochastic property of solar irradiance, which means that solar PV output is never fixed (despite monthly payments being fixed).
5. The stochastic nature of solar irradiance means that homes may not be able to meet even their basic energy-based needs due to non-availability of power, which potentially affects their quality of life (QoL) and socio-economic life.
6. Considering the limited usage options (in terms of electrical appliances) of the SHS compared to the wide usage option of the FBE, off-grid rural poor homes are further impoverished by having to purchase fuels (firewood and paraffin, for examples) from the SHS providers at commercial prices (as acknowledged by the policy) to meet their cooking and heating needs (DME 2009).

Based on these points, we start with the assertion that the current SHS system may not fulfil its intended purpose, and that the outcome has serious energy justice knock-ons. Thus, the remainder of this paper first explores the potential output of the SHS scheme and second, introduces a hybrid generation system that may reduce or remedy the above policy flaws. We close with an analysis of the justice benefits of this new model according the 5 principles introduced above.

3 Methodology: A brief on simulation data

Our first aim was to establish the expected output of the SHS rollout. In evaluating the power output of a typical SHS rollout across South Africa, we used data from nine (9) weather stations set-up by the Southern African Universities Radiometric Network (SAURAN) (Niekerk J. L. et al. 2015). SAURAN is an initiative of the Centre for Renewable and Sustainable Energy Studies (CRSES) at Stellenbosch University and the Group for Solar Energy Thermo-dynamics (GSET) at the University of KwaZulu-Natal and aims to make high-resolution, ground-based solar radiometric data available from stations located across the Southern African region, including South Africa, Namibia, Botswana and Reunion Island (*SAURAN*; Niekerk J. L. et al. 2015).

These nine (9) weather stations were located across seven provinces. We gathered data for one particular day - the 01/01/2016 - from 00:00 hours to 23:00 hours. The hourly data utilized are the Direct Normal

Irradiance (DNI) and temperature. Table 5 presents the weather stations, their location (city/province), latitude/longitude/elevation and code (alternate identification form). The weather stations chosen were those that had valid hourly data for the arbitrarily chosen day for simulation. The retention of weather stations within the same province is to show that weather variation is spatial even within a province.

3.1 SHS output power modelling

Table 6 presents the basic properties of the simulated solar panel. A utilization factor (fill factor) of 70% of the real-time maximum power is assumed. By utilization factor (fill factor) we mean the fraction of the real-time maximum power that can be harnessed based on converter settings. The solar panel is also assumed to be fixed while the converter settings are also fixed (i.e. no maximum power point tracking - MPPT). Figure 1 presents the typical Power-Voltage (P-V) characteristic of a solar panel and the concept of maximum power point tracking using the incremental conductance method Putri et al. 2015 while Figure 2 presents the typical representation of the SHS integration with each rural poor off-grid house. The profile of the typical daily utilizable power from the solar panel across the various weather stations is shown in Figure 3. The mathematical modelling of the SHS and the battery charging/discharging description is shown in Appendix I. For this paper, we assume that all solar power is initially directed into the battery before utilization. Table 7 presents the basic properties of the battery adopted in the simulation exercise.

According to DOE 2012a, p.28, the prevailing climatic condition of a geographic location plays an important role in determining the energy consumption pattern of households. Figure 4 depicts the radar plot of the daily utilizable power from the SHS across the provinces in South Africa. A critical observation of Figure 4 shows 3 classes of off-grid poor rural households that are - Class 1, Class 2 and Class 3:

- Class 1: This refers to the off-grid houses whose SHS daily output power is below the proposed 250 Wh/day. From the simulation carried out, Off-grid houses in Limpopo, Gauteng, KwaZulu-Natal and Free State fall under this class. Hence, $SHS_i^j \leq 250Wh/day$.
- Class 2: This refers to the off-grid houses in provinces whose SHS daily output was equivalent to or exceeded the proposed 250 Wh/day by about 50 Wh. Off-grid houses in western Cape fall under this class. Hence, $250Wh/day < SHS_i^j \leq 300Wh/day$.
- Class 3: This class consist of off-grid houses that have their SHS daily output exceeding 300 Wh/day. Off-grid houses in Eastern Cape and Northern Cape fall under this class. Hence, $300Wh/day < SHS_i^j$.

Where SHS_i^j is the SHS daily output power for house i in province j.

3.2 Justification for class discrimination

The classification of the houses into various classes (based on the SHS daily output as modelled) is for the following reasons:

- To show that output power from the SHS varies across and within the provinces. For example, for the same day of modelling, SHS output from $KZW - H$ is about $32Wh/day$ while it is $5.13Wh/day$ for $STA - H$ with both locations in the same province (KwaZulu-Natal).
- To show that many off-grid houses may not be able to get up to the proposed $250Wh/day$ due to spatial variations. For instance only 33% of the weather stations used for this research meet the $250Wh/day$ requirement.
- To highlight the contribution of the battery and inverter system in further depleting the SHS output power. It is seen from Tables 7 and 8 the battery and inverter specifications. In charging the battery, energy (up to 10%) is lost due to battery efficiency while the discharging of the battery for home use contributes further loss. Also, the battery continuously self discharges (albeit quite slowly) when left unused. These factors thus necessitate class distinction to highlight off-grid locations whose daily SHS power output can compensate for these losses.

Table 9 presents the typical electrical appliances ownership and usage description for an off-grid rural household utilizing the SHS. At 80% subsidy per month, this translates to about ZAR 12/month base cost ($cost_{base}^{low}$) paid by each household as running and maintenance costs. If $mSHS_{base}$ is the monthly base SHS power supply, then $c_{base}^{low/high}$ computation is shown in equation (1). QoL_{base}^{low} is fixed at 5 (with 80% subsidy considered). However, if subsidy is not considered, QoL_{base}^{high} is fixed at 0. Table 10 presents the evaluation of c_{base}^{low} for $QoL_{base}^{low} = 5$ and c_{base}^{high} for $QoL_{base}^{high} = 0$. For all cases, $mSHS_{base} = 7.5kWh$. Thus, in the computation of $c_{base}^{i,j}$ and $QoL_{base}^{i,j}$, SHS_i^j is always standardized to $mSHS_{base}$. Equation (2) presents the computation of $QoL_{base}^{i,j}$ while Table 11 presents the results (computation of $QoL^{i,j}_{base}$ and $c^{i,j}_{base}$) for all weather stations considered. Figure 5 presents the Duration-Comfort plot which shows the trade-off in comfort based on the duration (in days) it takes a household to receive $7.5kWh$.

$$c^{low/high}_{base} = \frac{cost^{low/high}_{base}}{mSHS_{base}}(ZAR/kWh) \tag{1}$$

$$QoL^{i,j}_{base} = \frac{QoL^{low}_{base}}{c^{low}_{base} - c^{high}_{base}}(c^{i,j}_{base} - c^{high}_{base}) \tag{2}$$

We ask at this stage, what constitutes basic electricity need? While the Non Grid Electrification Policy Guidelines for electrifying off-grid rural poor households is premised on supplying 250Wh/day, the analysis performed in this paper has shown that such target might not be feasible owing to geographic influence and the stochasticity of solar irradiance. Furthermore, the proposed SHS for off-grid rural poor homes impedes migration of households from lower energy levels to higher energy levels (through the acquisition of electrical appliances or extended usage of already owned electrical appliances). The Non Grid Electrification Policy Guidelines thus fail in guaranteeing energy security and availability for households. It is for this reason that the next section introduces the proposed hybrid generating system.

4 The proposed hybrid generation system

We now present our hybrid system for off-grid houses (Figure 6), which we argue, has the potential to provide more energy just outcomes to the current SHS system. The proposed hybrid generation system is a fixed site[4] generation scheme consisting of the solar PV modules, inverter system, converter system, battery and a diesel generator. It has a supply side energy management system (SSEMS) that performs MGA operations (for optimally scheduling LP5-LP7) and a smart load distribution board (SLDB) for each connected household. The following assumptions guide its operation:

- All the connected houses are assumed to be clustered together. This is to reduce losses owing to electricity distribution and the associated costs in extending supply to distant houses. A justification for this found in Linard et al. 2012 who state that "Several regions show a highly focal population distribution, with 90% of the population concentrated in less than 10% of the land surface, such as in South Africa."
- The pricing scheme adopted is flexible and easily adaptable.

The proposed hybrid generation scheme consists of u number of 50 Wp PV panels (where u is the number of connected off-grid houses), and 1 5-kVA diesel generator. The operation of the diesel generator is at specific times, 5am - 8am and 5pm - 10pm for weekdays and 5am - 8am, 11am - 2pm and 5pm - 10pm for weekends. Each connected house has a smart load distribution board which has pre-set load points that are controlled from the generation point. High energy demand points (cookers, pressing iron, electric kettles etc.) are connected to a fixed outlet point from the smart load distribution board which are only activated when the diesel generator is operational. This is to prevent the high energy demand loads from draining the battery supply. For the other times, the connected houses draw energy from the battery bank to meet such less energy demand needs as lighting, phone charging etc. Tables 12 and 13 present the dispatch of LP5-LP7 using MGA (see Appendix II) while Table 14 presents the monthly energy consumption of each considered house. The billing method adopted and the evaluation of the Q-point are presented in Appendix III, while Tables 15 and 16 present the monthly electricity allocation and monthly electricity bill per house for $Q - point = 4$. Figure 7 presents the Duration-Comfort plot for the proposed hybrid generation scheme for $n = 0$ while Figure 8 presents the progression of C_n and G_n (government monthly counterpart funding in form of subsidy for year n) for $Q - point = 4$.

4.1 Sensitivity analysis of the proposed hybrid generation scheme

In evaluating the economic and environmental impact of the proposed hybrid generation scheme in comparison to the SHS option (currently obtainable), we examine for the current community the extent to which the proposed hybrid generation scheme impacts on the energy burden[5] and carbon emissions of the community under consideration. As seen from Appendix IV, for the proposed hybrid generation scheme, if all houses belong to class 2, energy burden is evaluated to be about 13.92% with the proposed hybrid generation scheme reducing cumulative carbon emissions by 73%. Similarly, all houses belonging in class 6 results in an energy burden of 13.46% and a reduction in cumulative carbon emissions by over 40%. With regards to the risks of particulate pollution from diesel generation or negative health impacts, these can be mitigated, to some extent, by situating the generators outside the houses (on the settlement periphery) and not within homes (as is the

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[4] By fixed site we mean a centralized base of operations where electricity is generated before distribution to the connected houses.

[5] By energy burden we mean the fraction of a household's income spent on meeting its energy needs (CURES 2009).

case with cookstoves and firewood). While we acknowledge that our proposed system might not be an ideal one given its dependence on a fossil resource, we also acknowledge that 100% renewable is currently not feasible owing to the associated costs of sizing and the historical failures of such projects, as investigated by Azimoh et al. 2016 and Ikejemba et al. 2017. We note too, that the idea of incorporating diesel generators as a back up is not a new one (see Azimoh et al. 2016).

5 Results and discussion with respect to the energy justice framework

For the purpose of this paper, the following principles from Sovacool et al. 2016 energy justice framework are used to extending discussions on our simulation results.

- The availability principle [Principle 1];
- The affordability principle [Principle 2];
- The due process principle [Principle 3];
- The intra-generational equity principle [Principle 4];
- The sustainability principle [Principle 5];

5.1 Principle 1 discussion: Availability

The analysis of simulation results based on Principle 1 would transverse sufficiency of supply, security of supply, reliability of supply source, investment guarantee for sustainability and supply resilience. We thus seek to provide answers to the following questions:

- What constitutes sufficient energy of high quality [for the off-grid poor rural households]?
- Is there a disparity (energy-wise) between grid connected poor homes and off-grid poor homes?

Figure 4 shows the utilizable power from the SHS units across the provinces on a typical day. The implication of this is that in the seven provinces being considered, only GRT-H (Eastern Cape), SUT-H (Northern Cape) and VAN-H (Western Cape) are capable of meeting or exceeding the assumed 250 Wh daily production rates. The utilizable power produced in the other provinces is therefore *insufficient* in meeting the demands set out in Table 13. Furthermore, the stochastic nature of solar irradiance does not guarantee security and reliability of supply due to its unpredictable nature and variability in availability.

Considering the fact that under the Non Grid Electrification Policy Guidelines, the SHS are installed per household, monthly household collection rates are based on households' willingness to pay. This does not guarantee sustainable investment rates due to the risks involved in *recouping* investments. The huge costs involved in upgrading to the SHS systems also means that households cannot increase electricity consumption beyond the capacity of the installed SHS. Furthermore, the inability of the Non Grid Electrification Policy Guidelines to account for system depreciation irrespective of maintenance decimates households energy consumption capacity yearly, which has the potential of making households poorer energy wise in the long run.

According to Valer et al. 2017, 45kWh/month/household is currently the minimum for any electrification project that aims to receive funds from the *Conta de Desenvolvimento Energetico - CDE*. The 45kWh/month per household is evaluated and based on the assumption that this is the minimum energy required for lighting, communication and refrigeration. This value is similar to the 50-100kWh/year/person for basic energy needs in Sovacool et al. 2012, p.718 (if average household size for off-grid rural households is estimated at 4 persons/household). We thus evaluate the daily household basic energy need to be around 1.5 kWh/day (for 45kWh/month/household). While DME 2009 justifies the low capacity of the proposed SHS for off-grid poor homes by highlighting low energy consumption from previous electrification projects, it fails to create allowances for energy growth in off-grid poor rural homes owing to the mutual influence between demand and supply that exists when communities are electrified due to the purchase of new appliances (Valer et al. 2017).

The FBE offered to grid connected poor homes (rural or urban) is 50kWh/month, which resonates well with propositions in Valer et al. 2017; Sovacool et al. 2012. Yet none of the weather stations across the provinces considered achieves 25% of the FBE offer for grid-connected homes, creating or indeed compounding a disparity between grid connected and off-grid poor. This is due to the fact that the use of alternative energy sources such as firewood and paraffin for lighting, cooking and heating purposes would be proportionately *more* significant for the off-grid poor rural homes than the grid connected poor homes. In essence, for a number of reasons, the SHS does not fulfil the availability principle.

In contrast, by significantly improving the conventional system, the proposed hybrid generation system guarantees sufficient supply for lighting, entertainment and communication needs at the basic level with scheduled and regular intervention for more energy intensive needs (cooking, heating, ironing). The incorporation of an alternative energy source also guarantees the security and reliability of the supply, which makes it resilient to variations and fluctuations in solar irradiance. Investment wise, the proposed hybrid generation system coupled with its billing method guarantees its sustainability, making it attractive for investments. As seen from Tables 14 ($n = 0$) and 15 ($n = 0$ to $n = 9$), without additional system upgrades, the proposed hybrid generation scheme guarantees a minimum of 40.89kWh/month/household at $n = 0$ and 37.02kWh/month/household at $n = 9$ which creates some balance between grid connected and off-grid poor homes.

5.2 Principle 2 discussion: Affordability

In examining the simulation results under Principle 2, price stability and sustainable pricing capable of mitigating energy poverty would provide guidance for our discussions. Considering the multidimensional issues - pricing, energy poverty, energy vulnerability and QoL, we seek to provide answers to the following questions:

- Does electricity cost (based on unit cost) constitute energy poverty for homes?
- Is the SHS electricity bill justified based on variable supply?

According to STATSSA 2017, the poverty headcount in South Africa was 55.5% of the population in 2015. This was based on the upper-bound poverty line (UBPL) of ZAR 992/month. For the purpose of this paper, we define energy poverty (in terms of expenditure on energy) to be spending more than 12% of a households income on energy bills monthly. Considering the fact that the monthly cost of electricity for off-grid poor rural homes is about ZAR 12/month, this implies that on face value, only about 1.2% of a households income is spent on electricity needs from the SHS. However, STATSSA 2017, p.110 shows that annual expenditure of rural households on housing, water, electricity, gas and other fuels was 25% and 23.6% in 2011 and 2015 respectively. Further, Table 11 (column 3) shows that the "per unit" cost of electricity from the SHS for the provinces under consideration varied from ZAR 1.15/kWh to ZAR 77.97/kWh.

Considering the fact that many of the SHS's may not be operational and reliable (see Azimoh et al. 2016), off-grid poor rural households may be forced to source find alternative sources for most/all of their energy needs (e.g. lighting, cooking and heating) including paraffin and firewood. This thus increases the expenditure of households. According to DOE 2012a, about 47% of non-electrified households in South Africa experience energy poverty (using 10% household monthly income on energy as threshold).

The Duration-Comfort plot for the weather stations shown in Figure 5 presents a valid basis for further analysis. Using the expected 7.5 kWh/month - which is the proposed monthly supply for households from the SHS under the Non Grid Electrification Policy, there is a wide disparity between the comfort derived by households from the SHS and the duration it takes to receive 7.5 kWh. Electricity cost and monthly billing are thus not justified for the SHS under the Non Grid Electrification Policy. Moreover, the total dependence of most houses with the SHS on alternative fuel sources exposes them to the volatility of price fluctuations, which has the potential of further impoverishing these vulnerable groups.

Considering the fact that energy fuels and services are meaningless if households cannot afford to access and utilize them (Sovacool and Dworkin 2015), the proposed hybrid generation scheme adopts a sustainable and flexible billing system that is both progressive and adaptable. The yearly increment insures households from seasonal variations in prices of diesel while the guarantee of constant electricity for lighting and associated needs reduces households expenditure on alternative fuels. For example, Table 16 shows that the monthly expenditure of ZAR 214.74 guarantees households constant electricity for lighting, entertainment and communication and the daily scheduled supply for cooking and water heating purposes. Furthermore, the flexibility in utilizing lower-power rated electrical devices on higher-power rated points (LP7/LP6 or LP7/LP5 or LP4/LP6) reduces the inequity between House 4 and Houses 7 and 8 and also improves comfort as shown in the Duration-Comfort plot of Figure 7. In mitigating energy poverty, a monthly expenditure of ZAR 214.74 (21.6% of a monthly income of ZAR 992) drastically reduces off-grid poor rural households need for extra fuel, with implications for their QoL.

Where there are difficulties in establishing this system, government subsidy can play an active role in the proposed hybrid scheme through waivers or electricity price discounts for very poor homes (paid as a subsidy directly to the proposed hybrid scheme operator). However, this might not be feasible in the conventional system since the alternative to upgrading the SHS is subsidizing alternative fuel sources.

5.3 Principle 3 discussion: Due Process

In extending discussions on the simulation results obtained with respect to Principle 3, the level of community/stakeholders involvement and conflict resolutions through judicial and administrative remedies would form the core of our discuss. The questions to be answered include:

- How involved are the host communities in the execution of the SHS projects?
- Does the involvement of host communities portend sustainability of project?

According to Azimoh et al. 2017, a major contribution to the failure of the Lucingweni mini-grid project in South Africa was insufficient community engagement. The conventional system of SHS deployment creates no room for much community engagement since the SHS is tied to each house. Failure is thus guaranteed *ab initio* since any feedback from communities does not necessarily affect the technical and installation road maps. Furthermore, the issues of conflicts need not necessarily arise since households' SHS are independent of each other. Issues relating to maintenance and repairs are thus handled on a case-by-case basis.

Despite this, the proposed hybrid generation scheme still provides a better alternative as it improves on the failure of the Lucingweni project and the conventional SHS scheme for off-grid rural electrification by creating a model that allows for the active incorporation of the community. Since the success/failure of the proposed hybrid generation scheme is tied to the responsiveness of households in the community, the proposed hybrid generation scheme advocates for the creation of a community-led management responsible for computing electricity bills, allocating subsidies to households, penalizing households for failure to meet monthly obligations, determination usage savings accrued from excess solar irradiance and the like. The participation of the community through this community-led management may create a sense of 'shared ownership' since the project is deemed to be owned by all. The early engagement with the community regarding site selection and an environmental impact assessment (EIA) report is also necessary. In moderating resolutions, the ESCO along with the municipality act as unbiased members of the community-led management and provide technical and financial background to enable the community appreciate the long term goals of the proposed hybrid generation scheme. This line of argument is supported by the work of Chirenje et al. 2013 who state in the context of community participation and community based management in African case studies that "community participation was shown to be effective when the local population is involved not as co-operating users but as natural resource managers or owner managers."

5.4 Principle 4 discussion: Intra-generational equity

Principle 4, according to Sovacool and Dworkin 2015, argues for the right of people to access energy services fairly. In explaining further the simulation results from the perspective of Principle 4, we seek to address the issue of distributive justice by answering the following questions:

- What constitutes fairness in electrification exercises?
- To what extent should equity be applied in providing access (considering varying poverty levels)?

According to Islar et al. 2017, sufficientarianism holds that for a distribution to be deemed fair, all must receive sufficient amount of goods to meet their basic needs while egalitarianism deems a fair distribution as one in which all persons have equal share of goods. Navigating the conflicts arising thus necessitates the formulation of realistic targets with fair input from sufficientarianism and egalitarianism concepts. In trying to establish a baseline for the definition of basic needs, we are confronted with the 7.5 kWh/month (for the off-grid poor rural households under the Non grid Electrification Policy) DME 2009, 50 kWh/month (free basic electricity for grid connected poor homes) *GNESD*, 45 kWh/month Valer et al. 2017 and 50-100 kWh/person/year Sovacool et al. 2012. A critical analysis of the Non grid Electrification Policy from Table 9 shows that the guarantee of 250 Wh/day for off-grid poor rural households only avails residents of 4 hours electricity supply for television and lighting (assuming one CFL being operational for 4 hours) with very limited energy for phone and radio charging. A demerit of such a system is the fact that night time activities cannot be extended sufficiently to enable women perform home chores and allow school kids reading time. This negates the libertarian elements of freedom and choice as home users do not have choice in deciding to use available electricity or not since it is not initially sufficient. Furthermore, in terms of utilitarianism and welfare, the SHS system promoted by the Non Grid Electrification Policy contributes negatively to the QoL of households by providing no value for their investments to the SHS scheme due to varying and unpredictable weather conditions. Furthermore, the roll-out of a uniform rating of SHS across the provinces does not imply egalitarianism since our "realistic utopia" is constrained by an external condition - weather variation. In general, fairness is thus not derived from the Non grid Electrification Policy Guidelines.

A problem thus arises from the Non grid Electrification Policy in that an illusion of electrification is created for poor households in areas with poor solar irradiance thus depriving these off-grid poor rural households access to subsidized alternative fuel sources through the Free Basic Alternative Energy (FBAE) policy[6].

The proposed hybrid generation system provides a minimum of 40.89 kWh/month per household (assuming no depreciation) as seen in Table 15. This at the basic level is capable of guaranteeing 24-hours of lighting (for

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[6] The Free Basic Alternative Energy (FBAE) policy is a variation of the FBE and is aimed at supplying indigent off-grid households without SHS limited quantities of alternative energy fuels at no cost to meet their basic energy needs (see *DME*.)

4 CFLs simultaneously) and radio use, 1-hour of phone charging and 13 hours of television use for the basic household having LP1 (1 unit), LP2 (1 unit), LP3 (4 units) and LP4 (1 unit) on a weekday with extended usage (11.8% increase) on weekends. This satisfies sufficientarianism (since the basic provision meets the basic needs of lighting and entertainment sufficiently), egalitarianism (since based on our constrained utopia, basic electricity allocation is proportional to ownership of electrical appliances), libertarianism (since households have a choice over duration of use of devices though combination options under our constrained utopia is predefined) and utilitarianism (owing to the significant improvement in household welfare and QoL as evidenced from the Duration-Comfort plot in Figure 7). In ensuring that households have a sufficient level of electricity supply guaranteed across a day that can dispatch singly any of the load points (LP1-LP4), the proposed hybrid generation scheme is fair. Furthermore, the adoption of the proposed billing system for the hybrid generation scheme and the community-led management creates room for government interface and intervention (through subsidy for very poor households) to guarantee the minimum level of electricity supply (40.89 kWh/month assuming 0% depreciation). Thus, the determination of equity in electricity access for poor households does not arise since government's intervention guarantees them basic access.

5.5 Principle 5 discussion: Sustainability

In providing insights to our simulated results from sustainability perspective, we examine the frugality in the use of resources and the interaction of the generation scheme with the environment. We thus seek to provide answers to the following questions:

- Does the supply scheme inherently guarantee optimal usage of resources?
- How flexible is the supply scheme in adopting reparation measures that provide an option for system improvement in terms of sustainability?

According to Moner-Girona et al. 2016, the Clean Development Mechanism (CDM) under the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) permits industrialized countries having greenhouse gas reduction commitments to 'off-shore' investments in emissions reducing projects to developing countries as an alternative to costly reduction strategies in their countries. This thus underscores the need for sustainability and viability of emission reducing projects executed by developed nations in developing countries. According to DOE 2015, South Africa has received support from Danish Cooperation Programme (DANIDA), German Technical Co-operation Organization (GTZ), United Nations Development Programme (UNDP) and World Bank. The SHS installed in off-grid poor rural homes through the Non Grid Electrification Policy cannot be said to be sustainable especially when weather variations are incorporated. DOE 2015 further posits that about 96,000 SHS have been installed at an estimated cost in excess of ZAR 350 million with the SHS delivering quite limited services with lighting as the only quality service (over candles and paraffin lamps) DOE 2015, p.7. We can thus infer based on the limited services offered by the SHS (which is further decimated when weather variations are incorporated) that resources have not be optimally utilized. A justification for this stems from DOE 2015 where the redesigning of the entire off-grid electrification programme is being proposed to improve the quality of service (QoS) being offered through the establishment of a non-grid electrification authority. Furthermore, considering the isolated (per household) nature of the SHS installation, the conventional off-grid electrification scheme is not flexible enough to adopt reparation measures that would improve its QoS since that would come at a huge cost. While it may be argued that the SHS scheme does offer Certified Emission Reduction (CERs), this on the contrary cannot be substantiated considering the fact that in areas with poor solar irradiance, the SHS are of almost no importance since it depletes households income (through the once-off connection fee and monthly payments which do not obviate the need for households to still purchase alternative fuel sources to meet cooking, lighting and heating needs) and impacts negatively on households QoL (as shown in Figure 5).

The proposed hybrid generation scheme on the contrary through its flexible billing and centralized operations system coupled with the incorporation of an artificial intelligence tool (MGA) for optimization of load dispatch, ensures that resources are optimally utilized. This is evidently reflected in the sizing of the diesel generator and load dispatch (LP5-LP7) shown in Tables 12 and 13 for the various time slots. Furthermore, the proposed hybrid generation scheme incorporates a 15% carbon tax on diesel generator usage which could be aggregated and used in increasing the penetration of renewable energy (RE). The flexible billing system and centralized operations of the proposed hybrid generation scheme creates a platform for incorporating and experimenting a range of pricing and generation mix options which are capable of enhancing delivery and the robustness of the scheme. Additionally, the ability of the proposed hybrid generation scheme to compensate for excess solar irradiance through a re-adjustment of households monthly contribution can be deemed an off-grid feed in tariff system. The proposed hybrid generation scheme thus guarantees sustainability in terms of frugal utilization of resources and carbon emissions reduction by providing a platform that can make it accommodate government policies on emissions target and RE penetration.

6 Conclusions and policy implications

This paper offers the following conclusions. First, our study has argued that the Non Grid Electrification Policy may be practically and as a result, ethically flawed. As demonstrated based on an analysis using selected principles from the energy justice framework, the Non Grid Electrification Policy does not incorporate values into its delivery. Moreover, it does not adequately consider the effect of weather variations across and within the provinces on SHS output. Our simulated results have shown that solar irradiance stochasticity impacts heavily on the output of these SHS and deprives households their intended benefits. Moreover, the varying figures of 7.5 kWh/month/household for off-grid poor rural homes when compared to the FBE of 50 kWh/month/household for grid connected poor homes, 45 kWh/month/household from Valer et al. 2017 and 50-100 kWh/person/year from Sovacool et al. 2012 shows that it is quite inadequate in even fully dispatching the basic needs of lighting, entertainment and communication. In contrast, the proposed hybrid generation scheme we have presented has been shown to meet the requirements of the adopted principles from the existing energy justice framework and the ethical ideas of sufficientarianism, egalitarianism, libertarianism and utilitarianism in a realistic utopia.

Secondly, our study has shown that the Non Grid Electrification Policy inadvertently creates or reinforces poverty. Considering the poor contribution of the SHS to the QoL of households based on poor QoS and limited delivery of SHS, households spend more of their income in meeting their energy needs from alternative fuel sources since investments made toward the SHS scheme offer no additional value (see Figure 5). This thus exposes households to price volatility of these alternative fuel sources. Since productivity is linked to electricity access (Azimoh et al. 2017), declining electricity per capita as shown in Monyei and Adewumi 2017 and our arguments on the negative contribution of the SHS to QoL of off-grid poor rural households find support in STATSSA 2017 which shows increasing poverty across the country despite increasing generation capacity. Furthermore, the fixed nature of the SHS capacity prevents houses from transiting to higher energy levels through purchase of electrical appliances due to the inability of the existing SHS system to accommodate such. The proposed hybrid generation scheme however has been shown to guarantee productivity through provision of energy transition opportunities for households, stable and sufficient electricity supply and the adoption of a flexible billing and centralized operations system (that incorporates artificial intelligence tool (MGA) in optimally dispatching high energy loads).

Third, our study has shown that the Non Grid Electrification Policy is unsustainable. According to DOE 2015, a re-organization of the entire off-grid electrification programme is being proposed to improve system delivery. This resonates with simulation results obtained and arguments presented in this paper that (1) resources have been poorly utilized and deployed without proper sizing, adequate consideration of spatial variations and solar irradiance stochasticity; (2) upgrading the SHS to support energy transition of households is not sustainable (since it is capital intensive); (3) the long term operation of the SHS shows no consideration of depreciation and inflation indices which can potentially increase government's subsidy, decimate SHS performance and increase households contribution. The proposed hybrid generation scheme however improves on the conventional SHS scheme by providing a platform that can accommodate inflation and system depreciation and evolve a billing system to compensate for these (through the Q-point determination).

Fourth, our study has argued that the Non Grid Electrification Policy does not offer a platform for sufficient community engagement due to the isolated (per household) nature of SHS installations. Community engagement has been shown to be a contribution to the failure of the Lucingweni project and success of the solar-diesel Tsumkwe hybrid mini-grid project in Namibia (Azimoh et al. 2016; Azimoh et al. 2017). We have thus presented arguments supporting community-led management in contributing to decision making as regards the proposed hybrid generation scheme. Furthermore, we have argued that incorporating the community from the beginning and in all decision making processes creates a sense of 'shared ownership' which makes adoption of resolutions easily binding on all connected households.

Overall, this paper pioneers the incorporation of energy justice into off-grid electrification policy formulation for South Africa. Considering the planned overhaul of off-grid electrification programmes in South Africa, our proposed hybrid generation scheme offers a roadmap for off-grid electrification policy formulation especially in mitigating the impact of weather variations and guaranteeing a basic level of electricity supply that is available, affordable, sustainable and supports energy transition.

Finally, our paper has exposed the scarcity of sufficient research on the incorporation of values in power expansion programmes for South Africa, which thus necessitates further research. Considering the huge investments being made by Eskom in order to increase electricity supply capacity far beyond demand increase (see Monyei and Adewumi 2017), the worsening poverty (see STATSSA 2017) which we have argued is tied to decreasing electricity per capita (both for off-grid and grid connected households) and the capital intensive nature of off-grid electrification, ongoing research aims at creating a sustainable supply capacity expansion framework for Eskom that would lead to a significant reduction in planned electricity price increases, guarantee investment return for Eskom and free up resources for off-grid electrification projects.

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List of Tables

Table 2: Provincial population by population group for 2015 (X1000) (STATSSA 2015)

	Population group			
Province	Black African	Coloured	Indian/Asian	White
Western Cape	1967	3217	39	1022
Eastern Cape	5944	488	23	237
Northern Cape	638	455	2	87
Free State	2419	75	6	263
KwaZulu-Natal	9499	113	779	297
North West	3406	60	34	203
Gaunteng	10308	408	429	2123
Mpumalanga	3955	12	14	256
Limpopo	5509	33	38	74

Table 3: Provincial number of households by population group for 2015 (X1000) (STATSSA 2015)

	Population group			
Province	Black African	Coloured	Indian/Asian	White
Western Cape	894	1462	18	465
Eastern Cape	2702	222	10	108
Northern Cape	290	207	1	40
Free State	1100	34	3	120
KwaZulu-Natal	4318	51	354	135
North West	1548	27	15	92
Gaunteng	4685	185	195	965
Mpumalanga	1798	5	6	116
Limpopo	2504	15	17	34

Average household size of 2.2 is used (*ArcGIS*)

Table 4: Provincial households connected to the mains by population group for 2015 (X1000) (STATSSA 2015)

	Population group			
Province	Black African	Coloured	Indian/Asian	White
Western Cape	507	648	11	434
Eastern Cape	1213	117	5	88
Northern Cape	161	99	1	35
Free State	690	25	4	87
KwaZulu-Natal	1889	27	217	111
North West	913	22	7	79
Gaunteng	3004	110	112	675
Mpumalanga	982	4	3	74
Limpopo	1388	5	7	23

Table 5: Weather stations and their description (Niekerk J. L. et al. 2015)

S/N	**Code**	**Province**	**City**	**Latitude**	**Longitude**	**Elevation (m)**
1	UNV-H	Limpopo	Vuwani	-23.13	30.42	628
2	UPR-H	Gauteng	Pretoria	-25.75	28.23	1410
3	KZW-H*	KwaZulu-Natal	Durban	-29.82	30.94	200
4	STA-H*	KwaZulu-Natal	Umlazi	-29.97	30.91	95
5	UFS-H	Free State	Bloemfontein	-29.11	26.19	1491
6	GRT-H	Eastern Cape	Graaff-Reinet	-32.49	24.59	660
7	SUT-H	Northern Cape	Sutherland	-32.22	20.35	1450
8	RVD-H	Northern Cape	Alexander Bay	-28.56	16.76	141
9	VAN-H	Western Cape	Vanrhynsdorp	-31.62	18.74	130

* - 01/01/2017 data for station in KwaDlangezwa used

Table 6: PV panel specifications and parameter definition

Power	$50Wp^*$
n_{PV}	16%
Life cycle	25 years
V_{mp}	12 V
I_{mp}	4.1 A
n_s	40
n_p	1

* - from DME 2009. Other values are assumed.

Table 7: Battery specifications and parameter definition

Voltage	12 V
Rating	$105Ah^*$
n_{batt}	0.9
DOD	90%
σ	$<$ 3% per month
Life	3 years

* - from DME 2009. Other values are assumed.

Table 8: Inverter specifications and parameter definition

Voltage	12 V
Rating	500 W
n_{inv}	0.9

Values are assumed.

Table 9: Electrical appliances and duration profile

Need	Device	Number	Wattage (W)	Duration (Hrs)	Total consumption (W)
Lighting	CFL	4	6	-	21
Entertainment	TV	1	53	4	212
Others	Phone charging	1	10	-	5
	Radio	1	2	-	10

CFL-compact fluorescent lamp

Table 10: $QoL, c_{b}ase$ and duration values

	$QoL_{base}^{low/high}$	$c_{base}^{low/high}$	$mSHS_{base}$	duration(days)
low	5	1.6	7.5	30
high	0	8	7.5	30

Table 11: $QoL^{i,j}_{base}$, $c^{i,j}_{base}$ and duration evaluation for weather stations considered

Station	$QoL^{i,j}_{base}$	$c^{i,j}_{base}$	$mSHS_{base}$	duration(days)
UNV-H	3.69	3.28	7.5	61.52
UPR-H	1.82	5.67	7.5	106.32
KZW-H	-3.52	12.51	7.5	234.54
STA-H	-54.66	77.97	7.5	1461.93
UFS-H	4.23	2.58	7.5	48.44
GRT-H	5.26	1.27	7.5	23.84
SUT-H	5.35	1.15	7.5	21.56
RVD-H	4.21	2.61	7.5	49.02
VAN-H	5.21	1.33	7.5	24.93

Table 12: 5am-8am and 11am-2pm typical dispatch profile

		05:00-05:10	05:10-05:20	05:20-05:30	05:30-05:40	05:40-05:50	05:50-06:00	06:00-06:10	06:10-06:20	06:20-06:30	06:30-06:40	06:40-06:50	06:50-07:00	07:00-07:10	07:10-07:20	07:20-07:30	07:30-07:40	07:40-07:50	07:50:08:00
House 1	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	700	700	700	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 3	Cooker	0	0	0	0	0	0	0	0	0	750	750	750	750	750	750	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 4	Cooker	0	0	0	0	0	0	750	750	750	750	750	750	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	1000	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	700	700	700	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 5	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	1000	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 7	Cooker	0	750	750	750	750	750	750	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1000
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 8	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	750	750	750	750	750	750
	Electric kettle	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 10	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total (W)		1000	2150	2150	2150	1750	1750	1500	750	750	1500	1500	1500	1500	1500	1500	1750	750	1750

”0” signifies no dispatch for that time slot

Table 13: 5pm-10pm typical dispatch profile

		17:00-17:10	17:10-17:20	17:20-17:30	17:30-17:40	17:40-17:50	17:50-18:00	18:00-18:10	18:10-18:20	18:20-18:30	18:30-18:40	18:40-18:50	18:50-19:00	19:00-19:10	19:10-19:20	19:20-19:30	19:30-19:40	19:40-19:50	19:50-20:00	20:00-20:10	20:10-20:20	20:20-20:30	20:30-20:40	20:40-20:50	20:50-21:00	21:00-21:10	21:10-21:20	21:20-21:30	21:30-21:40	21:40-21:50	21:50-22:00
House 1	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	700	700	700	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 3	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	750	750	750	750	750	750	750	750	750	750	750	750	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 4	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	750	750	750	750	750	750	750	750	750	750	750	750	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	1000	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	700	700	700	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 5	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	1000	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 7	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	750	750	750	750	750	750	750	750	750	750	750	750	0	0	0	0	0	0
	Electric kettle	1000	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 8	Cooker	0	0	0	0	0	750	750	750	750	750	750	750	750	750	750	750	750	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	1000	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 10	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	1000
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total (W)		1000	1700	1400	1400	700	750	1750	1750	750	750	1750	1750	1500	2250	2250	2250	2250	2250	2250	2250	2250	2250	2250	2250	1500	1750	1750	750	1750	1000

"0" signifies no dispatch for that time slot

Table 14: Monthly house electricity consumption divided into source and week period

	Monthly house energy consumption				Total monthly (kWh)
House	PV/battery (kWh)	Generator (kWh)	Weekdays (kWh)	Weekends (kWh)	
1	22.09	41.66	44.47	19.29	63.76
2	22.09	18.8	29.07	11.82	40.89
3	22.09	84.05	70.32	35.82	106.14
4	23.64	129.03	102.72	49.95	152.67
5	22.09	38.8	43.74	17.15	60.89
6	22.09	18.8	29.07	11.82	40.89
7	23.64	106.16	87.32	42.48	129.8
8	23.64	106.16	87.32	42.48	129.8
9	22.09	18.8	29.07	11.82	40.89
10	22.09	38.8	43.74	17.15	60.89

Table 15: Standardized monthly allocation per house for $Q - point = 4$

House	House monthly standardized allocation (kWh/month) incorporating depreciation across the years									
	n=0	n=1	n=2	n=3	n=4	n=5	n=6	n=7	n=8	n=9
1	63.76	63.06	62.36	61.68	61.00	60.33	59.67	59.01	58.36	57.72
2	40.89	40.44	40.00	39.56	39.12	38.69	38.26	37.84	37.43	37.02
3	106.14	104.97	103.82	102.68	101.55	100.43	99.32	98.23	97.15	96.08
4	152.67	150.99	149.33	147.69	146.06	144.46	142.87	141.30	139.74	138.20
5	60.89	60.22	59.56	58.90	58.25	57.61	56.98	56.35	55.73	55.12
6	40.89	40.44	40.00	39.56	39.12	38.69	38.26	37.84	37.43	37.02
7	129.8	128.37	126.96	125.56	124.18	122.82	121.47	120.13	118.81	117.50
8	129.8	128.37	126.96	125.56	124.18	122.82	121.47	120.13	118.81	117.50
9	40.89	40.44	40.00	39.56	39.12	38.69	38.26	37.84	37.43	37.02
10	60.89	60.22	59.56	58.90	58.25	57.61	56.98	56.35	55.73	55.12
Total (kWh/month)	826.62	817.53	808.53	799.64	790.84	782.15	773.54	765.03	756.62	748.29

Table 16: Monthly electricity bill for each house using $Q - point = 4$

House	House monthly standardized payment (ZAR/month) for Q-point = 4 years									
	n=0	n=1	n=2	n=3	n=4	n=5	n=6	n=7	n=8	n=9
1	119.07	129.79	141.47	154.20	168.08	183.20	199.69	217.66	237.25	258.61
2	75.27	82.04	89.43	97.48	106.25	115.81	126.24	137.60	149.98	163.48
3	158.8	173.09	188.67	205.65	224.16	244.33	266.32	290.29	316.42	344.90
4	269.28	293.52	319.93	348.73	380.11	414.32	451.61	492.25	536.56	584.85
5	116.28	126.75	138.15	150.59	164.14	178.91	195.01	212.56	231.70	252.55
6	75.27	82.04	89.43	97.48	106.25	115.81	126.24	137.60	149.98	163.48
7	214.74	234.07	255.13	278.09	303.12	330.40	360.14	392.55	427.88	466.39
8	214.74	234.07	255.13	278.09	303.12	330.40	360.14	392.55	427.88	466.39
9	75.27	82.04	89.43	97.48	106.25	115.81	126.24	137.60	149.98	163.48
10	116.38	126.85	138.27	150.72	164.28	179.07	195.18	212.75	231.89	252.76
Total (ZAR/month)	1435.10	1564.26	1705.04	1858.50	2025.76	2208.08	2406.81	2623.42	2859.53	3116.88

List of Figures

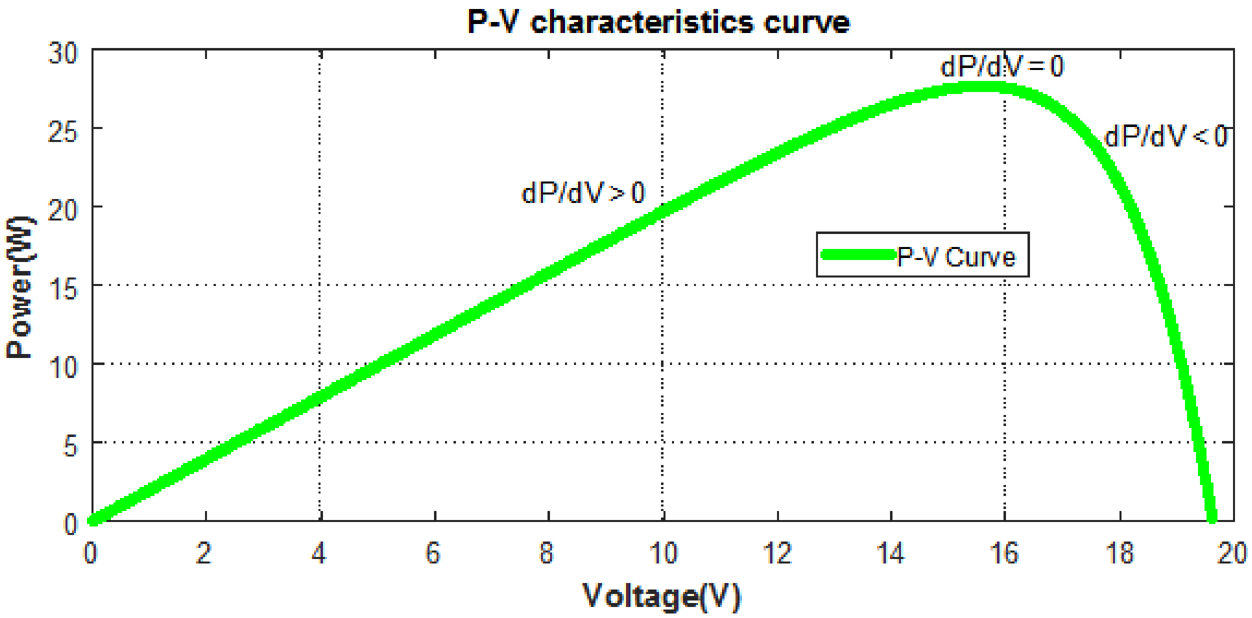

Figure 1: Solar panel typical P-V plot.

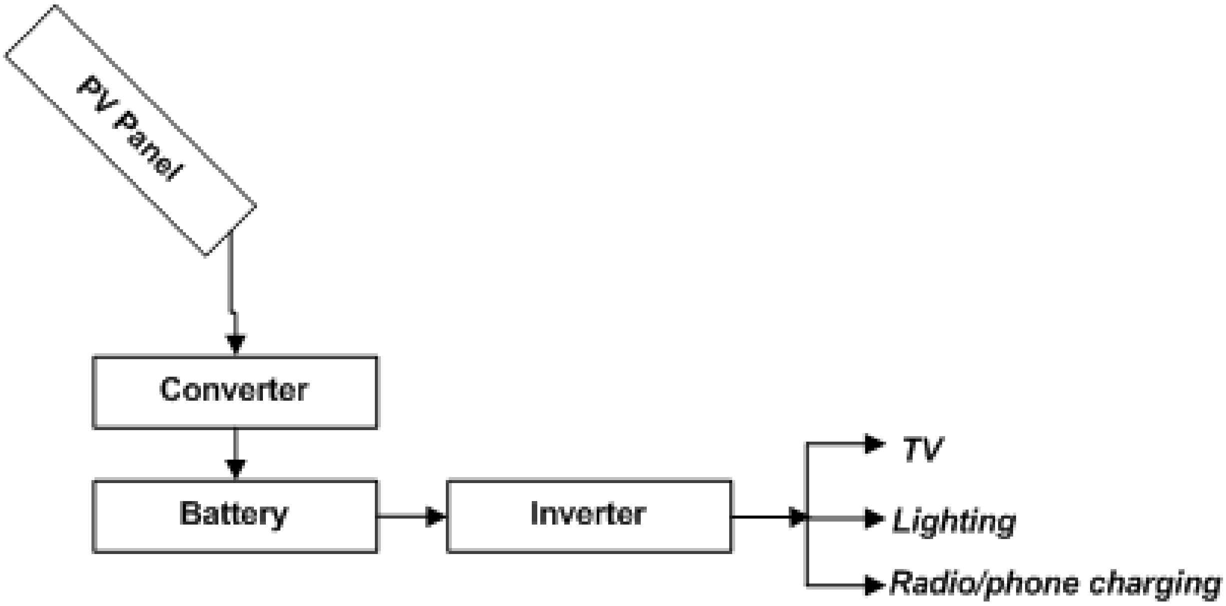

Figure 2: Singe house typical SHS integration.

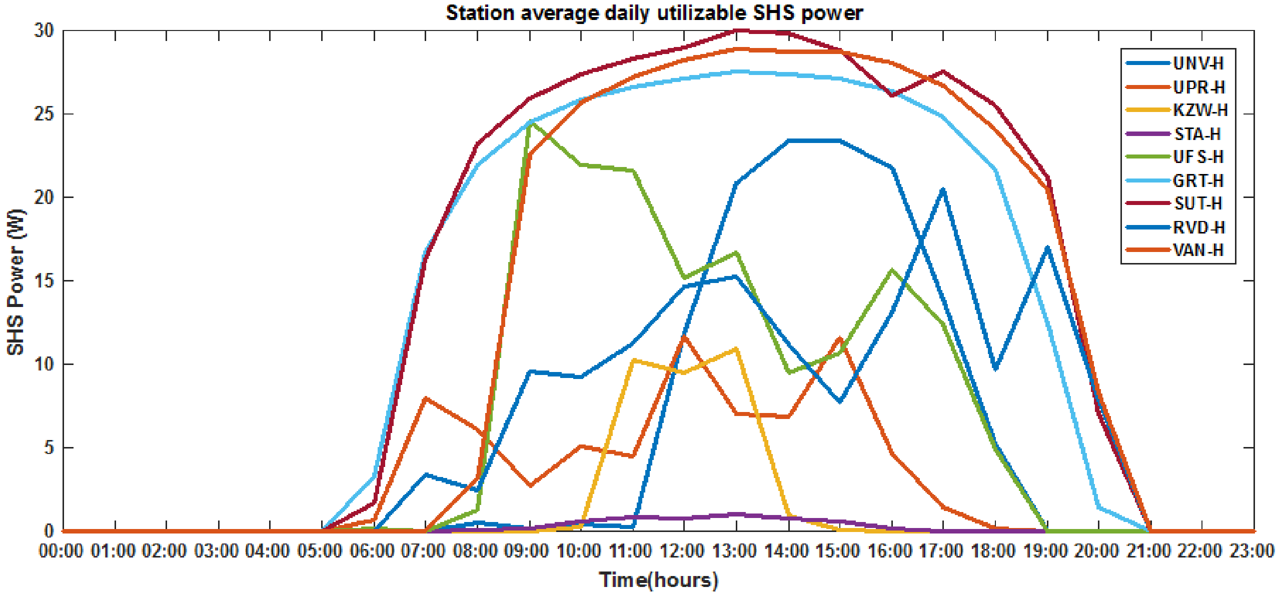

Figure 3: Daily utilizable power profile across the weather stations.

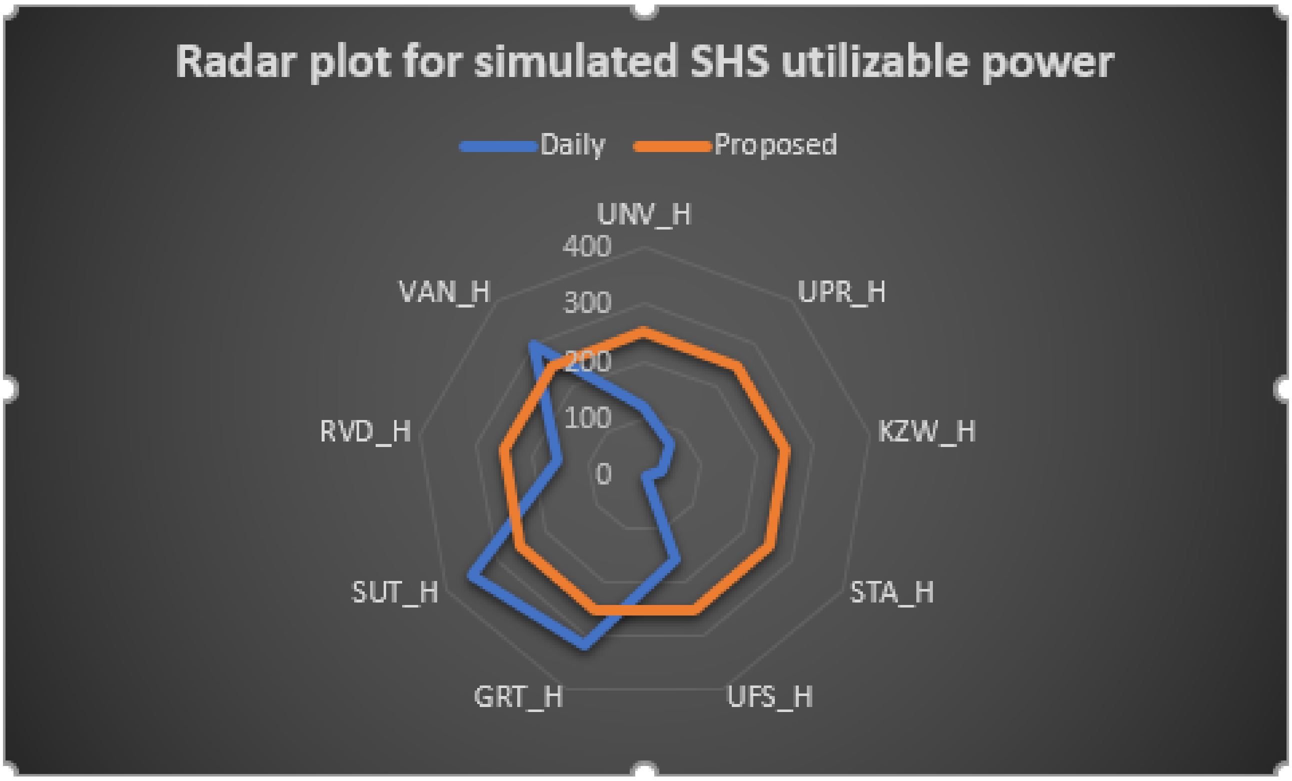

Figure 4: Radar plot of daily utilizable SHS power across the weather stations.

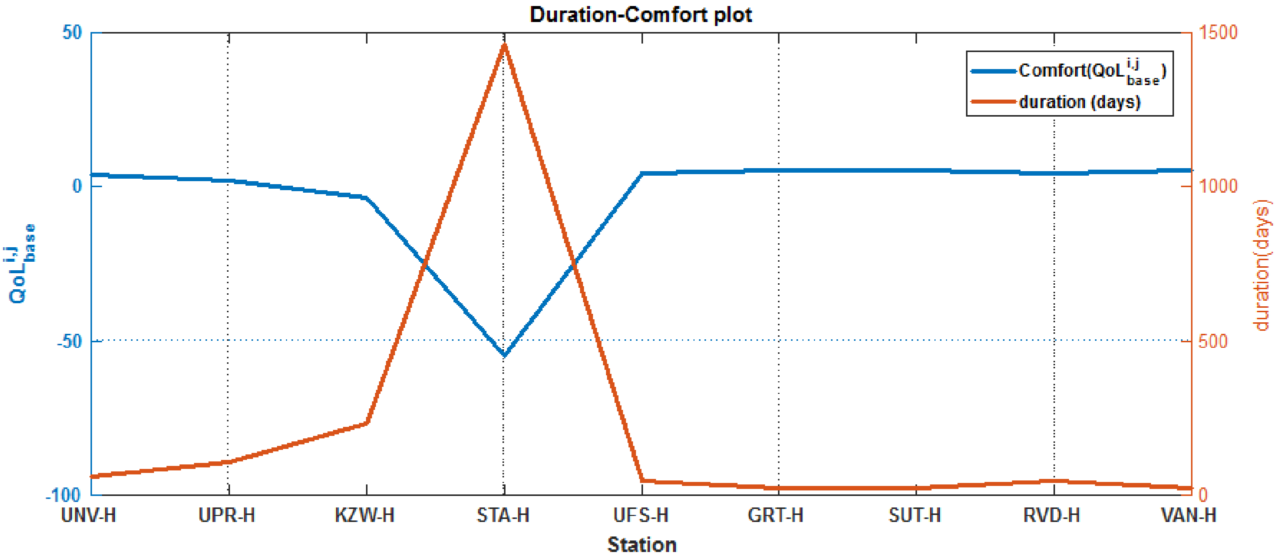

Figure 5: Duration-Comfort plot for weather stations.

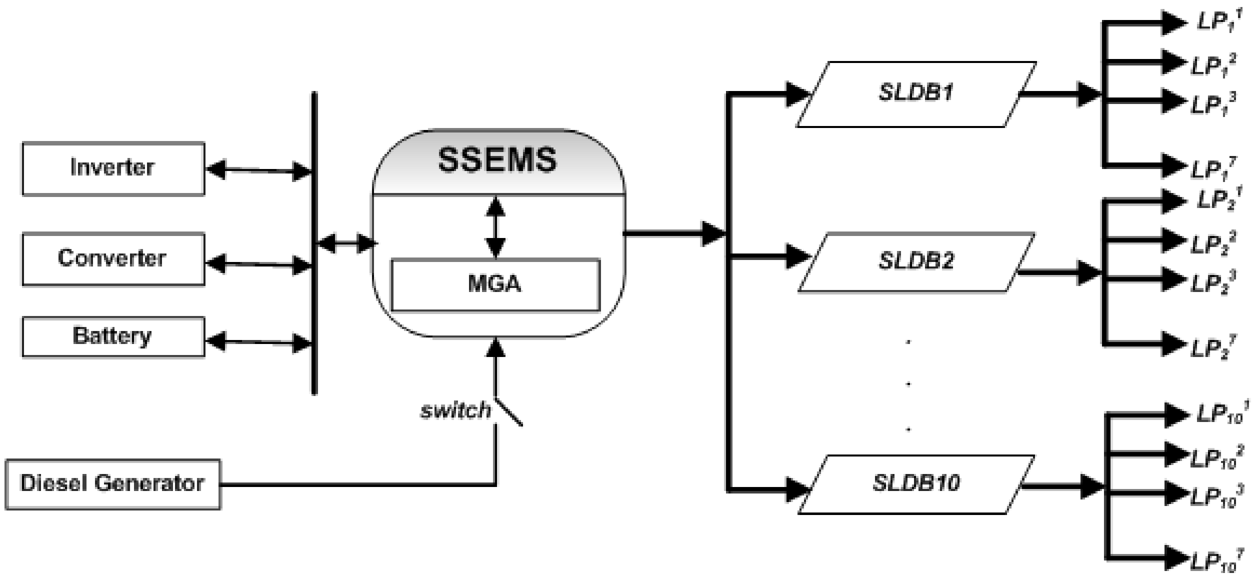

Figure 6: Proposed hybrid generation scheme.

Where $SLDBa$ is the smart load distribution board for house a; LP_a^b is the load point b for house a (where b could be a lighting point, television point, cooking point etc., see Monyei et al. 2016); SSEMS is the supply side energy management system and MGA is the modified genetic algorithm (Monyei and Adewumi 2017).

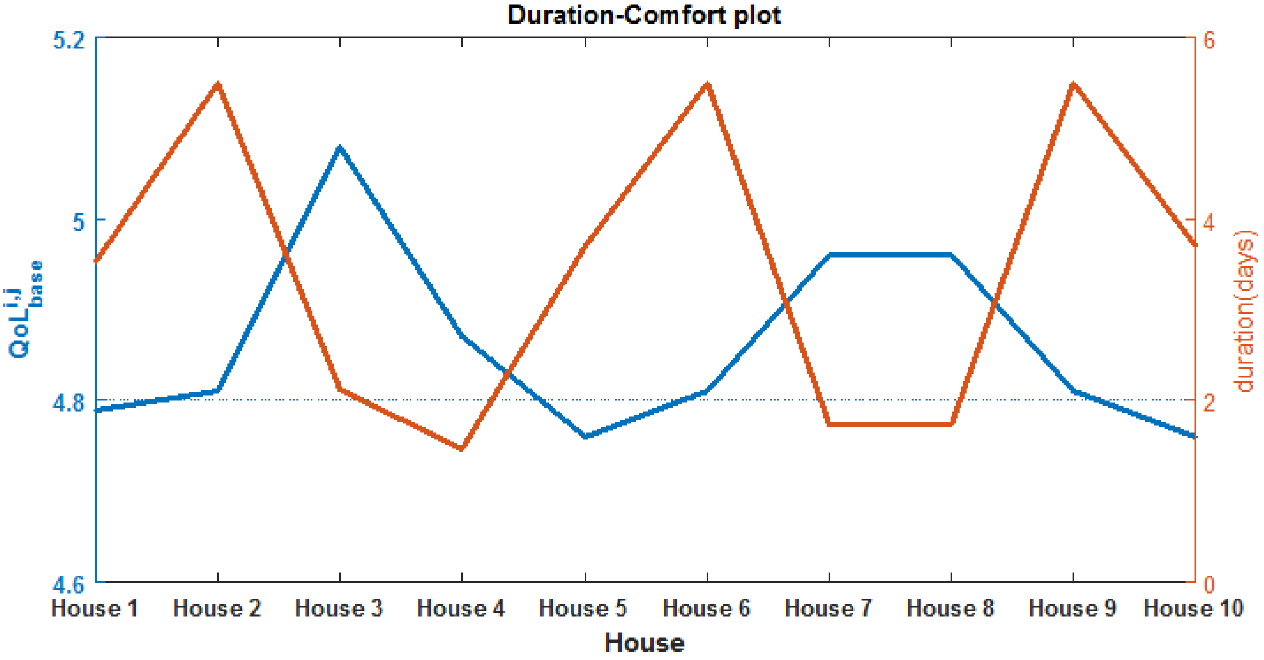

Figure 7: Duration-Comfort plot for all houses for $n = 0$.

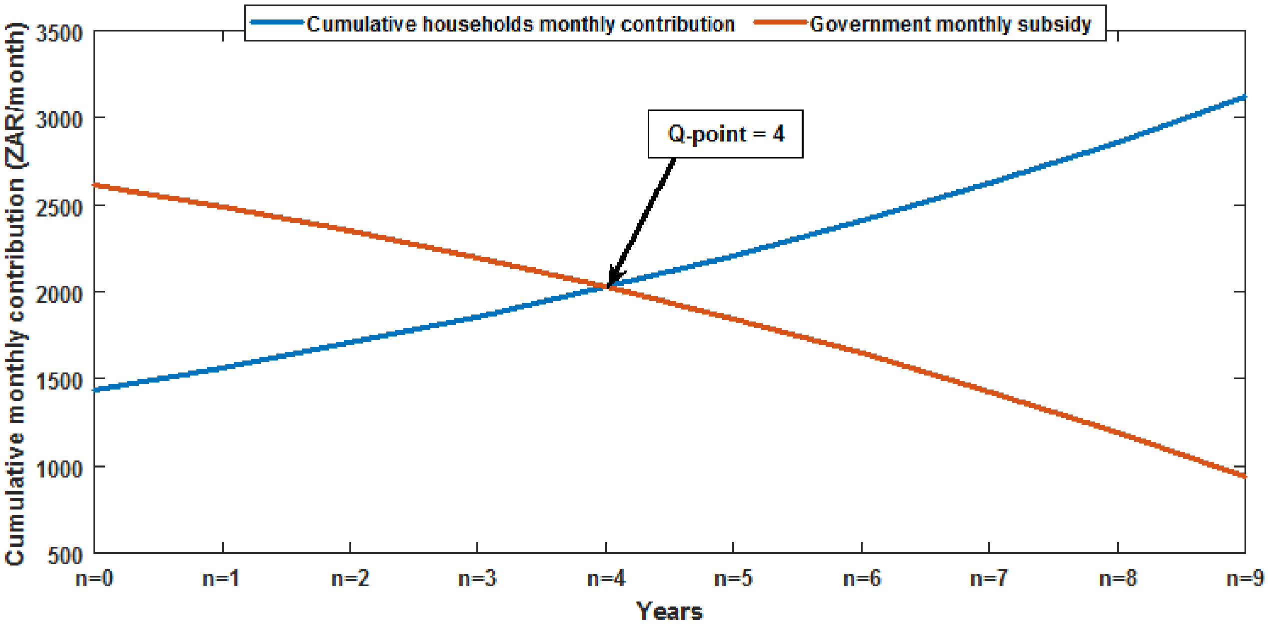

Figure 8: C_n and G_n progression plot.

Appendix I

Equation (3) presents the computation process of output (utilizable) power $P^{o/p}(t)$ at time t while equation (4) shows the relationship between ambient temperature (T) and T_c (i.e. conversion from ^oC to Kelvin).

$$P^{o/p}(t) = evaluate(T, V, G) \times V \times U_f \tag{3}$$

$$T_c = T + (0.2 \times G) + 273.18 \tag{4}$$

.

Where T is the hourly average weather station temperature (in Celsius), V is the fixed output voltage of the converter (12 Volts), G is the hourly average weather station irradiance (in Wm^{-2}) and U_f is the utilization factor (fill factor). The term $'evaluate'$ used in equation (3) is a function that computes hourly current (I in amperes) by utilizing the Newton-Raphson method.

For this paper, we assume that all solar power gets dumped into the battery first before utilization. Equation (5) shows the constraint on the battery state of charge $SOC(t)$ at any time t.

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{5}$$

Where SOC_{min} described in equation (6) is the minimum state of charge of the battery and is a function of battery's depth of discharge (DOD) and SOC_{max} is the battery's maximum state of charge. At maximum battery charge C_{batt}, $SOC(t) = SOC_{max}$.

$$SOC_{min} = (1 - DOD) \times C_{batt} \tag{6}$$

The law of energy conservation guides the battery charging and discharging operations and is described in equation (7).

$$SOC(t_{initial}) = SOC(t_{final}) \tag{7}$$

Where $SOC(t_{initial})$ is the battery state of charge at start of simulation and $SOC(t_{final})$ is battery state of charge at end of simulation. Given $P^{o/p}(t)$ as the PV output power at time t, n_{batt}, n_{inv} as efficiency of the battery and inverter respectively and σ as the battery discharge rate, then the equivalent of $P^{o/p}(t)$ dumped into the battery is given in equation (8). Given $D(t)$ to be real time demand, then its battery equivalent ($\overline{D(t)}$) is defined as $\overline{D(t)} = \frac{D(t)}{n_{batt} \times n_{inv}}$ where n_{inv} is inverter efficiency. If $\overline{D(t)} \leq SOC(t-1) \times (1 - \sigma)$ then Equation (9) describes the battery discharge.

$$SOC(t) = SOC(t-1) \times (1 - \sigma) + (P^{o/p}(t) \times n_{batt}) \tag{8}$$

$$SOC(t) = SOC(t-1) \times (1 - \sigma) - \overline{D(t)} \tag{9}$$

Appendix II

The aim of MGA (Monyei and Adewumi 2017) during generator operations is to constrain the allocation of loads (LP5-LP7) at any instant to less than 50% of the generator capacity. In doing this, time slots are pre-allocated to houses with loads LP5, LP6 and LP7 while every other load LP1, LP2, LP3 and LP4 gets dispatched with $df = 0.8$. Thus, if $slot^{max}$ is the maximum slot demand for any duration, equation (10) describes the MGA operation on the slot objective function (Z_{slot}).

$$Z_{slot} = min(slot^{max}) \tag{10}$$

Such that $slot^{max} = max(P_D)$, $P_D = \{P_D^k | k = 1 : k = 144\}$, $P_D^k = \sum_{i=1,k,j}^{i=10} \{LP5_k^{i,j}, LP6_k^{i,j}, LP7_k^{i,j}\}$ and $slot = \{k | k = 1 : k = 144\}$.

where $slot$ is a 10 minutes interval, P_D is the set of all slot power demands, P_D^k is the slot k power demand (W), k is the index of all slots and max is a function that finds the maximum value in a set. $LP5_k^{i,j}$, $LP6_k^{i,j}$ and $LP7_k^{i,j}$ are the households slot k dispatch value as computed by MGA. It must be pointed out that the slot k value for $LP5_k^{i,j}$, $LP6_k^{i,j}$ and $LP7_k^{i,j}$ are expressed by their power rating.

The artificial intelligence (AI) tool used for optimally allocating LP5-LP7 during hours 05:00-08:00 and 17:00-22:00 (for weekdays and weekends) and 11:00-14:00 (for weekends only) is the modified genetic algorithm (MGA) presented in Monyei and Adewumi 2017. In solving the dispatch problem (which is a minimization problem) as shown by equation (10), MGA is used to obtain the allocation of the varying combination of LP5-LP7 owned by the connected houses to obtain the minimum demand per time slot (10 minutes interval) possible. The results obtained are presented in Tables 11 and 12.

Appendix III

The billing of each household is as follows:

- PV cost: A flat rate of ZAR 60/month is billed each house for PV supply. This rate assumes the full cost due each house under the current SHS scheme for off grid houses by transferring the ZAR 48 cost paid by government (in form of subsidy) to the households.
- Generator cost 1: A special billing is applied to households owning any combination of loads LP5-LP7. Thus for any single ownership, a monthly flat rate of ZAR 20 is billed while ZAR 30 is billed for combination of any two (LP5/LP6, LP5/LP7or LP6/LP7). ZAR 48 is billed any house owning the three electrical appliances (LP5/LP6/LP7).
- Generator cost 2: In billing for generator use, houses owning none of LP5-LP6 are charged ZAR 0.65/kWh while houses owning either LP5, LP6 or LP7 are charged at ZAR 0.75/kWh. Houses owning either LP5/LP6 or LP5/LP7 or LP6/LP7 are charged at ZAR 0.94/kWh while houses owning LP5/LP6/LP7 are charged at ZAR 1.00/kWh.
- Generator cost 3: A 15% flat rate is applied on the billing for generator use (Generator cost 2) for all houses as environmental surcharge. This is the penalty due emissions from the diesel generator.
- Generator cost 4: A maintenance cost of 10% is applied on Generator cost 2 for all houses.

The implication of the strategy adopted for billing the houses means that monthly about ZAR 1,435.20 is recouped from the connected houses. However, the monthly expenditure on electricity generation (maintenance and operations) is ZAR 4,052.53. This means that the deficit of about ZAR 2,617.33 would be borne by the government in form of subsidy. Considering the increased expenditure by government in subsidizing off-grid electricity generation from the proposed hybrid generation model, we thus propose a quiescent point (Q-point) which defines the year at which contribution from the connected houses matches government's contribution. The establishment of a Q-point helps in determining the rate at which contributions from the houses would increase yearly. In modelling the Q-point, the following assumptions are made:

- 1: The monthly cost of generator maintenance has 0% yearly growth throughout the modelling period.
- 2: Power output from the generation station depreciates by 1.1% yearly.

Equations (11) and (12) model the yearly depreciation of generation power and combined household monthly contribution for each year.

$$P_n = P_{n-1}(0.989)^n \quad kWh/month \tag{11}$$

$$C_n = C_{n-1}(1 + \frac{rate}{100})^n \quad ZAR/month \tag{12}$$

Where, P_n and P_{n-1} are the present year n and preceding year $n-1$ power available for distribution while C_n and C_{n-1} are the present year n and preceding year $n-1$ combined monthly contribution from all the houses.

Tables 14 and 15 present the standardized monthly allocation (kWh/month) and monthly electricity bill (ZAR/month) for each household across the years under consideration using $Q - point = 4$ while Figure 7 presents the Duration-Comfort plot for $n = 0$. Figure 8 presents the progression of C_n and G_n (government monthly counterpart funding in form of subsidy for year n) for $Q - point = 4$.

Appendix IV

Table 17 presents the appliance ownership schedule for the houses under consideration. From Table 17, the houses can be grouped into 6 classes. The weekday and weekend demand profile for each house class is shown in Tables 18 and 19 respectively. Furthermore, Tables 20 and 21 show the pre-set time for the dispatch of the LP5-LP7 load points for weekdays and weekends respectively. The weekday and weekend energy allocation per house is shown in Tables 22 and 23 respectively while Table 24 presents the battery profile under the proposed hybrid generation scheme. Table 25 presents the monetary cost and equivalent carbon emissions for a typical household under consideration in meeting the needs LP1-LP7. It is observed from Table 25 that a typical household with a SHS and with a monthly income of R2000/month will expend about 18% (R357.61) monthly in dispatching LP1-LP7 with a monthly carbon emission $264.31 kgCO_2/house$.

However, for the hybrid generation scheme, Table 26 presents monthly associated cost for running the diesel generator and servicing the PV panels while Table 27 presents the equivalent monthly energy cost and equivalent carbon emissions for all the house classes. Figure 9 presents a pictorial representation of the variation of energy burden with carbon emissions for the various house classes. From Figure 9, house class ”0” represents a typical household with a SHS. A significant observation from Table 27 shows that if all houses belong to class 2, the hybrid configuration will result in a 73% drop in emissions over the SHS configuration. Similarly, all houses belonging to class 6 for the hybrid generation scheme will result in a 41% drop in emissions over the SHS configuration. It must be pointed out that the associated emissions from the SHS (i.e. PV and battery) have been ignored. Also, a typical summer month has been assumed (to account for the non-consideration of space heating).

Table 17: Electrical appliance ownership for the houses under consideration

House	TV LP1 53 W	Radio LP2 2 W	Lighting LP3 6 W	Phone charging LP4 10 W	Cooker LP5 750 W	Electric kettle LP6 1000 W	Iron LP7 700 W
1	$\checkmark^1$	$\checkmark^1$	$\checkmark^4$	$\checkmark^1$	X	X	$\checkmark^1$
2	$\checkmark^1$	$\checkmark^1$	$\checkmark^4$	$\checkmark^1$	X	X	X
3	$\checkmark^1$	$\checkmark^1$	$\checkmark^4$	$\checkmark^1$	$\checkmark^1$	X	X
4	$\checkmark^1$	$\checkmark^1$	$\checkmark^4$	$\checkmark^2$	$\checkmark^1$	$\checkmark^1$	$\checkmark^1$
5	$\checkmark^1$	$\checkmark^1$	$\checkmark^4$	$\checkmark^1$	X	$\checkmark^1$	X
6	$\checkmark^1$	$\checkmark^1$	$\checkmark^4$	$\checkmark^1$	X	X	X
7	$\checkmark^1$	$\checkmark^1$	$\checkmark^4$	$\checkmark^2$	$\checkmark^1$	$\checkmark^1$	X
8	$\checkmark^1$	$\checkmark^1$	$\checkmark^4$	$\checkmark^2$	$\checkmark^1$	$\checkmark^1$	X
9	$\checkmark^1$	$\checkmark^1$	$\checkmark^4$	$\checkmark^1$	X	X	X
10	$\checkmark^1$	$\checkmark^1$	$\checkmark^4$	$\checkmark^1$	X	$\checkmark^1$	X

X - implies not owned
$\checkmark^V$ - electrical appliance owned with v indicating quantity

Table 18: Weekday demand profile per group (per house)

Group	Number	Time			
		05:00-08:00	08:00-17:00	17:00-22:00	22:00-05:00
		df=0.8	df=0.6	df=0.8	df=0.6
1	3	213.6 Wh	480.6 Wh	712 Wh	373.8 Wh
2	1	1893.6 Wh	480.6 Wh	6312 Wh	373.8 Wh
3	1	2013.6 Wh	480.6 Wh	6712 Wh	373.8 Wh
4	2	2613.6 Wh	480.6 Wh	8712 Wh	373.8 Wh
5	2	4437.6 Wh	534.6 Wh	14792 Wh	415.8 Wh
6	1	6117.6 Wh	534.6 Wh	20384 Wh	415.8 Wh
Total (Wh)		24768 Wh	4968 Wh	82552 Wh	3864 Wh

Table 19: Weekend demand profile per group (per house)

Group	Number	Time					
		05:00-08:00	08:00-11:00	11:00-14:00	14:00-17:00	17:00-22:00	22:00-05:00
		df=0.8	df=0.6	df=0.8	df=0.6	df=0.8	df=0.6
1	3	213.6 Wh	160.2 Wh	213.6 Wh	160.2 Wh	712 Wh	373.8 Wh
2	1	1893.6 Wh	160.2 Wh	1893.6 Wh	160.2 Wh	6312 Wh	373.8 Wh
3	1	2013.6 Wh	160.2 Wh	2013.6 Wh	160.2 Wh	6712 Wh	373.8 Wh
4	2	2613.6 Wh	160.2 Wh	2613.6 Wh	160.2 Wh	8712 Wh	373.8 Wh
5	2	4437.6 Wh	178.2 Wh	4437.6 Wh	178.2 Wh	14792 Wh	415.8 Wh
6	1	6117.6 Wh	178.2 Wh	6117.6 Wh	178.2 Wh	20384 Wh	415.8 Wh
Total (Wh)		24768 Wh	1656 Wh	24768 Wh	1656 Wh	82552 Wh	3864 Wh

Table 20: Weekday pre-set duration

Load		05:00-08:00	17:00-22:00
Cooker	LP5	60 mins	90 mins
Electric kettle	LP6	10 mins	30 mins
Iron	LP7	30 mins	30 mins

Table 21: Weekend pre-set duration

Load		05:00-08:00	11:00-14:00	17:00-22:00
Cooker	LP5	60 mins	60 mins	120 mins
Electric kettle	LP6	10 mins	10 mins	20 mins
Iron	LP7	30 mins	20 mins	30 mins

Table 22: Weekday energy allocation per house

		05:00-08:00	08 : 00 – 17 : 00*	17:00-22:00	22:00-05:00	Sub-total	Total
House 1	LP1-LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	2021.40 Wh
	LP5-LP7	350 Wh	0 Wh	350 Wh	0 Wh	700 Wh	
House 2	LP1-LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	1321.40 Wh
	LP5-LP7	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	
House 3	LP1-LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	3196.40 Wh
	LP5-LP7	750 Wh	0 Wh	1125 Wh	0 Wh	1875 Wh	
House 4	LP1-LP4	237.60 Wh	378 Wh	396 Wh	415.80 Wh	1427.40 Wh	4669.07 Wh
	LP5-LP7	1266.67 Wh	0 Wh	1975 Wh	0 Wh	3241.67 Wh	
House 5	LP1-LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	1988.07 Wh
	LP5-LP7	166.67 Wh	0 Wh	500 Wh	0 Wh	666.67 Wh	
House 6	LP1-LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	1321.40 Wh
	LP5-LP7	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	
House 7	LP1-LP4	237.60 Wh	378 Wh	396 Wh	415.80 Wh	1427.40 Wh	3969.07 Wh
	LP5-LP7	916.67 Wh	0 Wh	1625 Wh	0 Wh	2541.67 Wh	
House 8	LP1-LP4	237.60 Wh	378 Wh	396 Wh	415.80 Wh	1427.40 Wh	3969.07 Wh
	LP5-LP7	916.67 Wh	0 Wh	1625 Wh	0 Wh	2541.67 Wh	
House 9	LP1-LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	1321.40 Wh
	LP5-LP7	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	
House 10	LP1-LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	1988.07 Wh
	LP5-LP7	166.67 Wh	0 Wh	500 Wh	0 Wh	666.67 Wh	

* - insufficient battery capacity resulting in reduction in pre-set allocation

Table 23: Weekend energy allocation per house

		05:00-08:00	08:00-11:00	11:00-14:00	14:00-17:00	17:00-22:00	22:00-05:00	Sub-total	Total
House 1	LP1-LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	2410.73 Wh
	LP5-LP7	350 Wh	0 Wh	233.33 Wh	0 Wh	350 Wh	0 Wh	933.33 Wh	
House 2	LP1-LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	1477.40 Wh
	LP5-LP7	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	
House 3	LP1-LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	4477.40 Wh
	LP5-LP7	750 Wh	0 Wh	750 Wh	0 Wh	1500 Wh	0 Wh	3000 Wh	
House 4	LP1-LP4	237.60 Wh	178.20 Wh	237.60 Wh	178.20 Wh	396 Wh	415.80 Wh	1643.40 Wh	6243.40 Wh
	LP5-LP7	1266.67 Wh	0 Wh	1150 Wh	0 Wh	2183.33 Wh	0 Wh	4600 Wh	
House 5	LP1-LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	2144.07 Wh
	LP5-LP7	166.67 Wh	0 Wh	166.67 Wh	0 Wh	333.33 Wh	0 Wh	666.67 Wh	
House 6	LP1-LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	1477.40 Wh
	LP5-LP7	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	
House 7	LP1-LP4	237.60 Wh	178.20 Wh	237.60 Wh	178.20 Wh	396 Wh	415.80 Wh	1643.40 Wh	5310.07 Wh
	LP5-LP7	916.67 Wh	0 Wh	916.67 Wh	0 Wh	1833.33 Wh	0 Wh	3666.67 Wh	
House 8	LP1-LP4	237.60 Wh	178.20 Wh	237.60 Wh	178.20 Wh	396 Wh	415.80 Wh	1643.40 Wh	5310.07 Wh
	LP5-LP7	916.67 Wh	0 Wh	916.67 Wh	0 Wh	1833.33 Wh	0 Wh	3666.67 Wh	
House 9	LP1-LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	1477.40 Wh
	LP5-LP7	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	
House 10	LP1-LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	2144.07 Wh
	LP5-LP7	166.67 Wh	0 Wh	166.67 Wh	0 Wh	333.33 Wh	0 Wh	666.67 Wh	

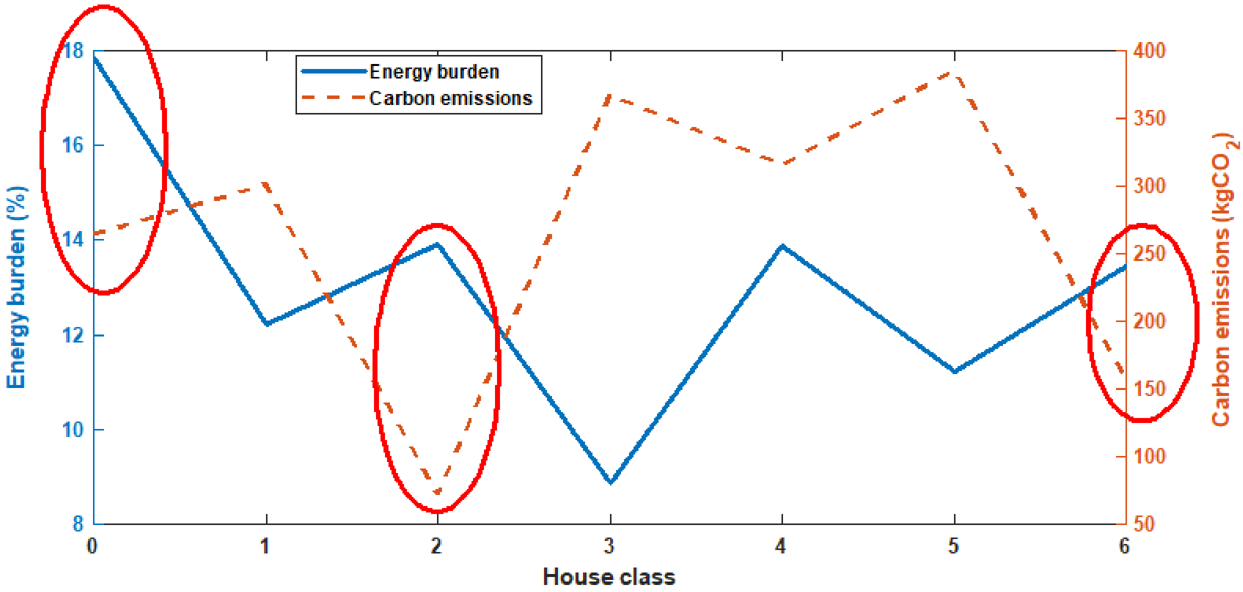

Figure 9: Energy burden versus Emissions variation for the various house classes.

Table 24: Battery profile under the proposed hybrid generation model

5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-1	1-2	2-3	3-4	4-5
Battery capacity (%) without generator																							
10.00*	10.00*	10.00*	10.00*	10.02	10.06	10.12	10.17	10.24	10.29	10.32	10.33	10.32	10.31	10.30	10.29	10.28	10.27	10.27	10.00*	10.00*	10.00*	10.00*	10.00*
Weekday battery capacity profile (%) with generator																							
20.00	30.00	40.00	40.00	40.02	40.06	40.12	40.17	40.24	40.29	40.32	40.33	48.32	56.31	64.30	72.29	80.28	80.27	80.27	80.20	80.14	80.07	80.01	79.95
battery charging - generator only			battery charging - PV only									battery charging - generator only					utilization and derating only						
Weekend battery capacity profile (%) with generator																							
20.00	30.00	40.00	40.00	40.02	40.06	43.12	46.17	50.24	50.29	50.32	50.33	58.32	66.31	74.31	82.31	90.31	90.27	90.27	90.19	90.12	90.05	89.98	89.91
battery charging - generator only			battery charging - PV only			battery charging - PV and generator			battery charging - PV only			battery charging - generator only					utilization and derating only						

* - battery maximum depth of discharge

battery capacity is 1050 Ah

Table 25: Energy needs cost and emissions computation under SHS configuration

Energy need	Alternative	Cost (ZAR)	C02 emissions (kgC02)
LP1	kWh (est.)	41.95	
LP2	kWh (est.)	41.95	
LP3	Candles[a]	58.73	5.13
LP4	kWh (est.)	33.56	
LP5	Paraffin[b]	151.02	0.54
LP6	Wood[c]	8.40	6.05
LP7	Coal[d]	10.00	252.51
Monthly surcharge		12.00	
Total		357.61	264.31

[a] - $C0_2$ emission is taken to be $10.69gC0_{2e}$ from Weston 2008. 2 candles per household for 8 hours duration daily is assumed. 1 Month is taken to be 30 days.

[b] - cost is taken from CURES 2009 and adjusted at 1.6779% cumulative inflation rate. $C0_2$ emissions is taken to be $2.58kgC0_2/L$.

[c] - cost is taken from CURES 2009 and adjusted at 1.6779% cumulative inflation rate. $C0_2$ emissions is taken to be $1.8kgC0_2/kg$.

[d] - Cost is assumed and $C0_2$ emissions taken to be $2419kgC0_2/Tonne$.

Table 26: Monthly operations cost for diesel generator and SHS maintenance cost

Weekdays	$8hours \times 22days = 176hours$
Weekends	$11hours \times 8days = 88hours$
Total monthly hours	264 hours
Diesel cost	ZAR 11.50/Litre
Hourly diesel rate	1.2 Litres/hour
Monthly diesel cost	ZAR 3643.20/month
Monthly generator maintenance	ZAR 400
Monthly SHS maintenance	ZAR 9.33
Total monthly cost	ZAR 4052.53

Table 27: Energy cost and emissions for the hybrid generation scheme

Class	Houses	Cost (ZAR)			Emissions (kgC02)		
		Hybrid scheme	Others	Total	Hybrid scheme	Others	Total
1	2,6,9	75.27	169.42	244.69	42.00	259.10	301.10
2	1	110.07	159.42	278.49	65.49	6.59	72.08
3	3	158.80	18.40	177.20	109.02	258.56	367.58
4	5,10	116.28	161.02	277.30	62.54	253.05	315.59
5	7,8	214.74	10.00	224.74	133.32	252.51	385.83
6	4	269.28	0.00	269.28	156.81	0.00	156.81