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Electricity for development: Mini-grid solution for rural electrification in South Africa

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Abstract

The objective of most rural electrification programs in the developing world is to bring about socio-economic development to households. Governments have put in place a number of measures to achieve this goal. Previous studies on rural electrification programs in developing countries show that solar home systems and mini-grid systems are the dominant technologies. Assessments of a pilot hybrid mini-grid project at Lucingweni village have concluded that mini-grid projects are not feasible due to high electricity production costs. As a result efforts towards rural electrification have been focused on the solar home system. Nevertheless, previous studies of the South African solar home system program have shown that the development objectives of the program are yet to be met more than a decade after commissioning. Therefore, this study investigates the viability of a hybrid mini-grid as a solution for rural development in South Africa. Investigations were based on Lucingweni and Thlatlaganya, two rural Villages where the mini-grid and solar home system have been introduced. The mini-grid systems were designed taking into consideration available natural resources and existing load profiles. The results show that a village of 300 households needs about 2.4 kWh/household/day of electricity to initiate and sustain income generating activities and that the solar home system is not capable of supporting this level of demand. We also show that in locations with hydro resources, a hybrid mini-grid system has the most potential for meeting the energy needs of the households in a cost effective manner. The assessment shows that with adequate planning and optimization of available resources, the cost of electricity production can be reduced.

Keywords: Mini grid; Solar Home System; Rural Electrification; Techno Economic Analysis; Power quality; Grid Extension Breakeven Distance.

1. Introduction

Even though the Millennium Development Goals (MDG)[1] did not specifically mention access to modern energy and clean cooking facilities among its goals, the realization of both is key to the achievement of the MDG [1]. The world energy outlook shows that about 1.3 billion people have no access to electricity and about 2.7 billion people still rely on biomass for cooking. More than 95% of these people are either in sub-Saharan Africa or developing Asia, and about 84% live in rural areas [2]. Previous reports have shown that there is a close link between energy access and economic development [3]. Reliable access to electricity has been shown to be a precondition for improving livelihoods in remote rural households [4]. Another study stated that access to electricity will lead to sustainable development and environmental conservation [5]. Despite this, sub-Saharan Africa and developing Asia remain outliers in world energy usage trends [6]. The objective of a majority of rural electrification programs in developing countries is to bring about socio-economic development to poor households. Various measures have been adopted

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[1] In September 2000 world leaders came together at the UN headquarters in New York to adopt the Millennium Development Declaration to reduce extreme poverty by the year 2015. The most prominent goal is to halve the proportion of people who live of less than 1$ a day by 2015. The other goals concern universal education, gender equality, child health, maternal health, combating HIV/AIDS, environmental sustainability and the creation of a global partnership for development.

by the affected governments to improve energy access to their off-grid populations, but they have met with little or no success. A review of rural electrification programs in developing countries shows that the Solar Home System (SHS) is the foremost decentralized technology used to improve access to energy in rural communities [7].

SHS is attractive due to its apparent cost-effectiveness, as most un-electrified households are in remote rural and peri-urban areas where access to the grid is financially non-viable [7]. However, assessment of the development impacts of SHS has also revealed some negative results [8]. An investigation of the developmental impact of the SHS program in Bangladesh found little evidence to show that electricity from SHS supports development [8]. A review of the effectiveness of SHS called into question, the use of public funds to drive SHS programs at the expense of other appropriate technologies [7]. Another review of SHS programs in several countries concluded that despite the social and environmental benefits, the economic viability remains uncertain [9].

The South African SHS program was launched in line with the policy objectives of the Integrated National Electrification Program (INEP), which is aimed at increasing energy access to deprived households after the abolition of apartheid. The program initially focused on extension of the national grid, but after the first phase of the program (1994-1999) it became obvious that urban settlers felt greater benefits than rural dwellers [10]. This was because Eskom (the main national utility company), who funded the program, found it economically unviable to extend the grid to remote rural areas due to the low income of the inhabitants, dispersed homesteads and low energy demand [10]. Therefore, due to its comparative advantages over the alternatives, SHS was chosen as the preferred technology to electrify rural households [11].

One of the basic elements of INEP is the Free Basic Electricity (FBE) policy, which is aimed at providing electricity access to all South Africans [10]. This policy seeks to address ways and means through which government interventions can bring about socio-economic development to disadvantaged households [12]. For this reason SHS has been used for rural electrification in most remote rural settlements in the non-grid zone[2] of South Africa for more than a decade.

The SHS program has not achieved this status through its performance, but partly due to huge government spending and the resilience of the Energy Services Companies (ESCOs). The national budget for electrification shows that as of 2013, about ZAR 58 million had been spent on the SHS program, and about ZAR 91 million was budgeted for the SHS program in 2014 [13]. Since the inception of the program in 2002 only about 68,115 households out of the original target of 500,000 households earmarked for SHS installations have had the system installed [13].

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. Furthermore, the sustainability of the program is facing several challenges which have led to three out of the six energy providers ceasing operations, with another on the verge of opting out [14].

The inability of SHS to meet the energy needs of rural households and the policy objectives of FBE, as well as the uncertain sustainability of the program motivate the

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[2] In the South African context, non-grid zones are those areas that do not have foreseeable access to the grid. They are located far from the grid and sometimes in mountainous terrains.

search for an alternative energy solution that can meet the energy needs of the rural off-grid populations. Hybrid mini-grid systems have been found to have potential for productive use in Colombia [15]. They also have the potential to alleviate poverty in rural households [16]. However, the use of hybrid mini-grids in rural electrification programs in developing countries has not been widespread due to high investment costs and technical complexity. The low incomes and energy demand of rural households also limits the willingness to invest. This situation lends credence to the argument that a confluence of public and private investments and good regulations are necessary for successful implementation of mini-grid projects in rural communities [15]. A previous study of a hybrid mini-grid project at Lucingweni village in South Africa concluded that mini-grids are not viable due to the high electricity production cost, and that the economies of scale for renewable energy favour the national grid [5]. The Lucingweni mini-grid did not work beyond three months after commissioning, due to the high levelized cost of electricity (LCOE), which was higher than users were willing to pay [5]. An evaluation of the Lucingweni mini-grid project showed that a feasibility study, holistic understanding of the technology’s life cycle and energy needs crucial to ensure sustainability of the project, were missing [17]. Another report opined that since sustainability of projects depends on the ability of customers to pay for services, measures towards local economic development are essential [13].

Experience has shown that for a rural electrification program to be sustainable, it must be able to improve the payment capability of the beneficiaries [18]. The argument against the use of the mini-grid system in South Africa has been based on its high electricity production cost. The issues of low power capacity of SHS and its limited socio-economic development impact on rural households have received little attention. Furthermore, less attention has been given to the mini-grid alternative, partly due to the failure of the Lucingweni pilot mini-grid project and the notion that mini-grids are not feasible in South Africa due to the reported high electricity production cost [5]. This study is focused on the use of hybrid mini-grid systems as an alternative solution to meet the energy needs of rural households in South Africa.

In addition, due to the limited success of SHS in bringing development to rural households, this paper also investigates:

-The ability of hybrid mini-grid systems to extend the availability of power to rural households without compromising on quality and reliability, so that productive and thermal energy needs are met sustainably.

- The optimal energy mix needed to produce electricity at the lowest cost in two South African villages where mini-grid and SHS have been introduced.

-The techno-economic justification for including the mini-grid solution in the South African rural electrification program.

-How the cost of electricity production in the mini-grid system could be reduced.

2. Methods and materials

The methods used in this study are illustrated in Figure 1.

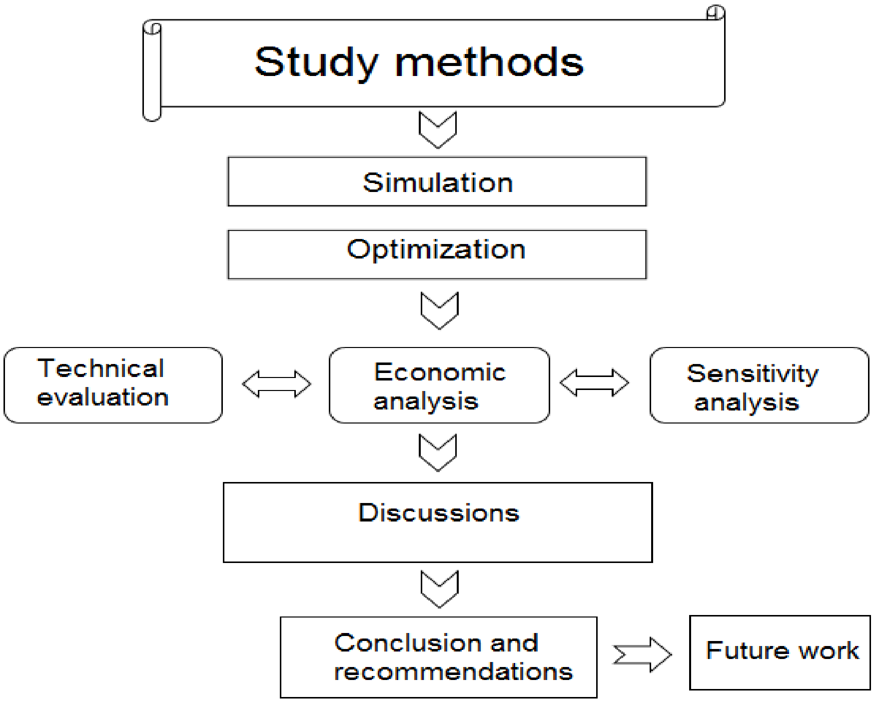


Figure 1: The research methods used in the study

A case study was performed at two locations in South Africa, Thlatlaganya village in Polokwane municipality, Limpopo province (23.5°S and 29.4°E), and Lucingweni Village (32.11°S and 28.46°E) in Eastern Cape Province. System optimization was used to harness the best energy mix from the natural resources available at the two sites. The weather data for the two villages was obtained from the closest station to each village using HOMER™ and RETScreen™ software, i.e. Polokwane for Thlatlaganya and Butterworth for Lucingweni village, at 60 m altitude above sea level and anemometer height of 10 m. Simulations were carried out with 60 minute time steps.

The average load (0.543 kWh/day) was based on the standard usage pattern of the SHS system at Thlatlaganya village [16], and the load data for the mini-grids was adapted from [5], based on data from the Lucingweni pilot mini-grid project. 300 households were used as the base case in this study, in line with the South African census figure of 2011 for Thlatlaganya village. The load profile for the two villages was designed to meet the energy needs for domestic use, commerce, agriculture, carpentry, metal works, primary and secondary schools and health services.

Evaluation of the economic viability of the hybrid mini-grids was done using financial instruments such as levelized cost of electricity (LCOE), net present cost (NPC), Initial Capital Cost (ICC), operating cost (OC), operation hours (OH), rate of fuel consumption and breakeven grid extension distance (BED). The optimal energy mix and the economic viability of the mini-grid for the two locations were obtained through an optimization process using HOMER™ hybrid energy software. A sensitivity analysis of the systems was performed to assess the impact of varying diesel cost and wind speed on the economics of mini-grid systems. The technical analyses in this investigation were also based on HOMER™ energy model simulations. The power quality of the mini-grids was assessed using the state of charge (SOC) of the battery as an indicator. The expected impact of the electricity from the hybrid mini-grids in Thlatlaganya and Lucingweni was compared with the current state of the SHS program in Thlatlaganya village. The HOMER™ model has been used to assess the feasibility of using renewable hybrid systems to electrify remote rural villages in Cameroon [19], to analyze electricity costs in Rawdat Ben Habbas village in Saudi Arabia [20], and to assess the performance and reliability of a standalone hybrid wind-solar-battery system [21]. It has also been used to compare the techno-economics of SHS and PV micro grids [22] and a range of hybrid and centralized systems [23]. HOMER™ energy model uses the following equations for the techno-economic evaluation of mini-grids.

The total power output $P(t)$ from various technologies and energy sources is calculated using equation (1)

$$P(t) = \sum_{S=1}^{N_S} PV_S + \sum_{W=1}^{N_W} P_W + \sum_{H=1}^{N_H} P_H + \sum_{G=1}^{N_G} P_G \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where PV_S is the electrical power output from the photovoltaics (PV), and P_W, P_H and P_G are the electrical outputs from wind, hydro and diesel generators respectively.

The LCOE is calculated using equation (2)

$$LCOE = \frac{CRF(i,N).C_{NPC} - C_{boiler} H_{served}}{E_{served}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1}$, is the capital recovery factor, i is the interest rate (%), N is the number of years, C_{NPC} is the total net present cost ($), C_{boiler} is the marginal cost of the boiler ($/kWh), H_{served} is the total thermal load served (kWh/yr) and E_{served} is the total electrical load served (kWh/yr). However, the boiler is excluded in this study, and thus the right side of the numerator is zero while the left side represents the annualized cost of electricity.

The total electrical power output from the hydro turbine is given by equation (3)

$$P_H = \frac{\eta_H \cdot \rho_{water} . g \cdot h_{net} \cdot Q_{turbine}}{1000 W/kW} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

Where $\eta_H$is the hydro turbine efficiency (75%), ρ_{water} is the density of water (1000 kg/m^3), g is the acceleration due to gravity (9.8 m/s^2), h_{net} is the effective water head (25 m),and $Q_{turbine}$ is the hydro turbine minimum flow rate (0.25 m^3/s). Minimum flow rate (Q_{min}) is given in equation (4)

$$Q_{min} = W_{min} . Q_{design} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

Where,

W_{min} is the minimum flow ratio (50%) and Q_{design} is the designed flow rate (0.5 m^3/s). The available flow to the turbine is the difference between the total stream flow and the residual flow rate.

The total electrical power output from the PV is given by equation (5)

$$PV_S = Y_{PV} f_{PV} \left(\frac{G_T}{G,STC}\right) [1 + \alpha_P \left(T_C - T_{C,STC}\right) \ldots\ldots\ldots\ldots \tag{5}$$

Where f_{PV} is PV derating factor [%], Y_{PV} is the PV rated capacity [kW], G_T is the incident global irradiation (kW/m^2), G, STC is the incident radiation under standard test conditions (1 kW/m^2), α_P is temperature coefficient of power (%, °C), T_C is PV cell temperature [°C] and $T_{C,STC}$ is PV cell temperature under standard conditions (25 °C).

Generator (diesel) total electrical power output is adapted from equation (6)

$$F = F_0 . Y_{gen} + F_1 . P_{gen} \ldots\ldots\ldots\ldots \tag{6}$$

Where, $P_G$is the electrical output of the generator, F is the fuel consumption rate (l/h), F_0 is the fuel curve intercept coefficient ($L/h/kW_{rated}$), Y_G is the rated capacity of the generator (kW), and F_1 is the fuel curve slope ($L/h/kW_{output}$).

The state of charge of the battery system in a hybrid mini-grid during discharge is given in equation (7) [24].

$$Pb(t-1).(1-\sigma) - (\frac{Ph(t)}{\eta_i} - P_l(t) \ldots\ldots\ldots\ldots \tag{7}$$

The state of charge when the battery is charging is given in equation (8).

$$Pb(t-1).(1-\sigma) + \left(P(t) - \frac{P_l(t)}{\eta_i}\right).\eta_b \ldots\ldots\ldots\ldots \tag{8}$$

Pb (t-1) and P_b (t) are the battery energy at the beginning and the end of the interval t respectively, P_l (t) is the load demand at the time t, Ph (t) is the total energy generated by PV array, diesel and wind generators at time t, σ is the self-discharge factor and η_b and η_i are the battery charge and inverter efficiency (80% and 90% respectively) as obtained from HOMER™ data.

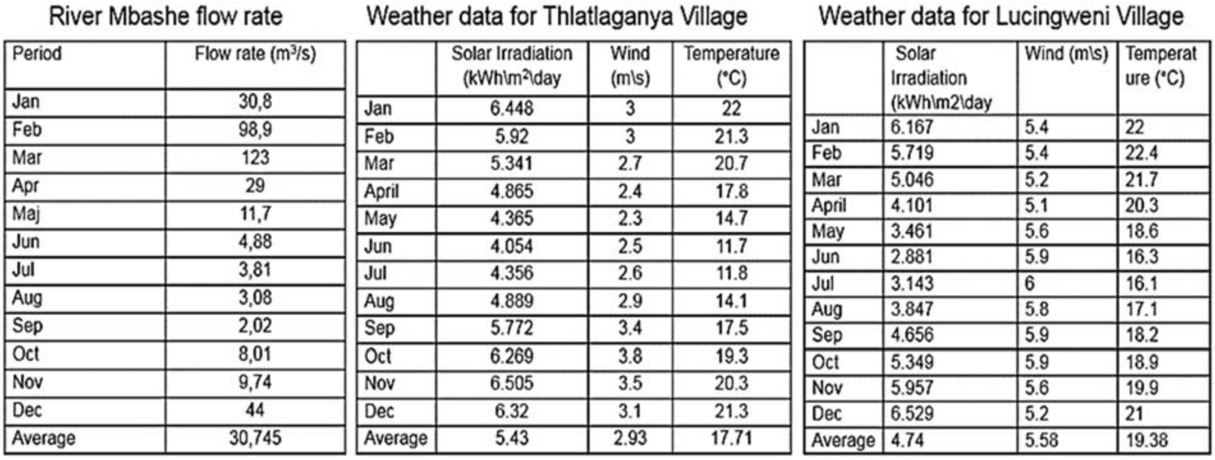
2.1 Description of the two study areas

Thlatlaganya village is situated several kilometers from Polokwane in Polokwane municipality in the Limpopo province of South Africa. Thlatlaganya is one of the villages under the South African SHS concession program. According to the population census of 2011 there are around 300 households in Thlatlaganya village, with an average of 4 inhabitants per household. The elderly rely mostly on pension income for subsistence. The young depend mostly on subsistence farming and daily paid jobs, while the unemployed rely on grants from relatives and well-wishers. The national grid is available at the periphery of Thlatlaganya village, and most households that can afford the connection fees are connected. Most of those who can afford the Eskom connection fees and tariffs are middle income earners, comprising mainly of retirees and those who alternate living between the city and the village. The poorer members of the community who cannot afford the fees depend on SHS for electricity.

The wind profile of Thlatlaganya village indicates an average of 2.93 m/s and the average daily solar irradiation is 5.43 kWh/m2/day. The annual average ambient temperature is 17.7°C (Table 1). The SHS used at Thlatlaganya consists of a 75 WP solar panel, a charge controller, and a 100Ah, 12 V battery system.

Lucingweni village is situated in the Transkei region in Ndayeni municipality within OR Tambo district municipality in the Eastern Cape Province of South Africa. The inhabitants are mostly Xhosa tribespeople, the main occupation is farming, and most people depend on agriculture for subsistence. The elderly depend on pensions and grants for their income. As well as the advantage of proximity to the coast and thus high wind speeds, Lucingweni also has high solar irradiation. The average wind speed is 5.6 m/s and average daily solar irradiation is 4.74 kWh/m^2/day. The annual average ambient temperature is 19.38°C. The flow rate of the Mbashe River at the nearby Mpozolo village based on 2014 hydrology data was used as the hydro resource for the study [25]. The records show an average flow of 30.75 m^3/s with the highest flows recorded in February and March, and the lowest flow in September (Table 1). The Lucingweni pilot mini-grid project was the first of its kind in South Africa. It was designed to supply electricity to 220 households, using 6 x 6 kW wind turbines, 560 x 100 W solar panels, 10140 Ah battery storage, 12 x 2.5 kW inverters and 4 x 15 solar regulators [5].

Table 1: Mbashe River 2014 flow rate



River Mbashe flow rate

Period	Flow rate (m^3/s)
Jan	30,8
Feb	98,9
Mar	123
Apr	29
Maj	11,7
Jun	4,88
Jul	3,81
Aug	3,08
Sep	2,02
Oct	8,01
Nov	9,74
Dec	44
Average	30,745

Weather data for Thlatlaganya Village

	Solar Irradiation (kWh\m^2\day	Wind (m\s)	Temperature (°C)
Jan	6.448	3	22
Feb	5.92	3	21.3
Mar	5.341	2.7	20.7
April	4.865	2.4	17.8
May	4.365	2.3	14.7
Jun	4.054	2.5	11.7
Jul	4.356	2.6	11.8
Aug	4.889	2.9	14.1
Sep	5.772	3.4	17.5
Oct	6.269	3.8	19.3
Nov	6.505	3.5	20.3
Dec	6.32	3.1	21.3
Average	5.43	2.93	17.71

Weather data for Lucingweni Village

	Solar Irradiation (kWh\m2\day	Wind (m\s)	Temperature (°C)
Jan	6.167	5.4	22
Feb	5.719	5.4	22.4
Mar	5.046	5.2	21.7
April	4.101	5.1	20.3
May	3.461	5.6	18.6
Jun	2.881	5.9	16.3
Jul	3.143	6	16.1
Aug	3.847	5.8	17.1
Sep	4.656	5.9	18.2
Oct	5.349	5.9	18.9
Nov	5.957	5.6	19.9
Dec	6.529	5.2	21
Average	4.74	5.58	19.38

2.2 Costs of components and materials used for calculations in the study

The costs and materials used in the study were based on published data from international organizations and reports from local institutions (Table 2).

Table 2: Costs of components and materials

Cost of electricity in South Africa [$/KWh]	0.06 [26]
Cost of grid extension [$/km]	23,000.00 [27],[28]
Cost of diesel [$/l]	0.9 [26]
Cost of Hydro, replacement and O&M [$/KW]	1,300.00, 870.00 and $100/yr. [29]
Cost of Wind, replacement and O&M [$/KW]	1,500.00, 1,400.00 and $0.03/yr. [30]
Cost of PV, replacement and O&M [$/KW]	4,000.00, 3,500.00 and 0.00 [31]
Cost of battery, replacement and O&M [$/KWh]	300.00, 300.00 and $10.00/yr. [32]
Cost of converter, replacement and O&M [$/KW]	900.00, 700.00 and 0.00 [33]
Interest rate South Africa	5.75% [34]
Inflation rate South Africa	6.21% [35]

2.3 Assumptions and limitations of the study

It was assumed that: the prevailing foreign exchange rate at the time of the investigation was $1 USD to ZAR 10; the load usage pattern was the same for every household; the mini-grid and SHS project lifetimes were both 25 years; and security lights were the only source of energy consumption during the night.

The limitations of the study were: non-availability of primary data on the actual cost of components used for the implementation of the hybrid mini-grid project, leading to reliance on international published data; absence of the actual usage pattern in the load profile therefore the load profile was based on an estimate of the average household loads;

limited options for reducing the excess electricity produced with the hydro turbine since only one model is available in HOMER™ Hybrid Energy Software.

3 Results

3.1 Technical evaluation of the mini-grid and solar home system

Technical evaluation of the systems was intended to compare the integrity of power provided by the mini-grid with that from SHS given the low power capacity of the system which hampers its ability to support income generating activities.

3.1.1Electricity production capability of the Thlatlaganya mini-grid and the Solar Home System

Analysis of the designed mini-grid system show that the amount of electricity demand of the households is 732 kWh/day representing about 2.4 KWh/day/household. The peak load in the morning corresponds to an increase in domestic activities such as water heating, ironing and cooking of breakfast. There is high electricity usage between 08:00 and 18:00 which is necessary to support productive activities during the day (Fig. 2). The base load occurs mostly at night, during which the supply only has to power street lights and household security lights. The total load for each household using SHS in Thlatlaganya is 0.543 kWh/day, while the total load for the 300 households is 163 kWh/day. Peak loads occur in the morning and in the evening corresponding to lighting, radio and TV use at these times. The base load between 08:00 to 18:00 is an indication of minimal activities during the day, when the only demand is from charging phones and radio use.

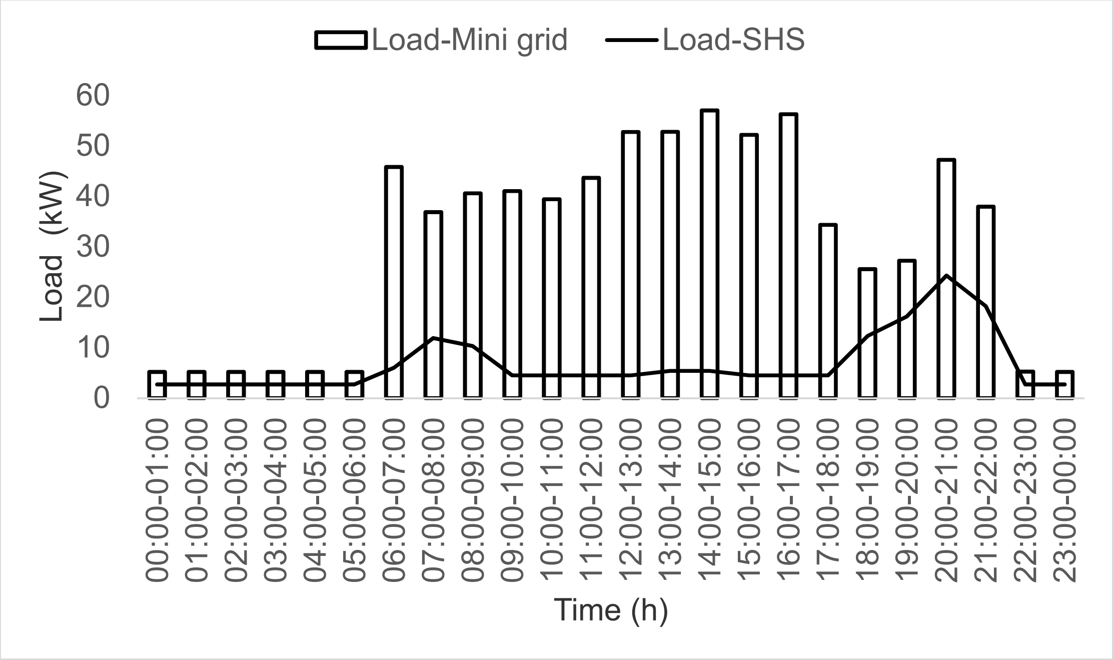


Fig. 2 Load profile for mini-grid and the solar home system.

3.1.2 Comparison of activities supported by mini-grid and SHS

The assessment of the operation of the mini-grid system shows that it is able to extend electricity availability to the households for 24 hours, supporting activities such as lighting, refrigeration, agriculture (irrigation, milling), carpentry, education, health, security services and other small scale enterprises. This is in contrast to the SHS which supplies intermittent electricity for around 3 to 5 hours per day and is used mostly at night for lighting and entertainment purposes (Table 3).

Table 3: Activities supported by SHS and the mini-grid system

Energy Source	Load Type	Supported Activities	Domestic activities	Energy availability
SHS (0.543 kWh/HH)	black & white television, electric bulbs, cell phone charging, and small radios	light is used for mat making at night, small retail shops, hair plaiting and barbering at night	Lighting, entertainment, listening to news and communication using radio and phone	3-4 hours per day
Mini-Grid (2.4 kWh/HH)	colour television, electric bulbs, electric iron, refrigerator, air conditioner, cell phone charger, water pump, milling machine, electric saw, planner, welding set, grinder, compressor, drilling machine, sewing machine, personal computer, printer, scanner, hair drier, hair clipper etc.	agriculture through irrigation, carpentry, cyber cafe, ice making, water pumping, clinic, welding, primary & secondary schools, hair salon, etc.	lighting, cooking, Ironing, entertainment, communication, air conditioning, street lights, etc.	24 hours per day

3.1.3 Energy mix and technology choice

The optimization of the energy resources available at Thlatlaganya show that the optimal energy mix for the hybrid mini-grid system is a combination of a 50 kW diesel generator (50 kW Genset), 14 kW PV, 140 kW wind generator (Generic10kW), 150 kW converter and 400 kWh battery system which combine to meet the 732 kWh/day energy demand. The PV and wind generator provide 20% of the energy mix, with the remainder being provided by the diesel generator (Fig. 3). Optimization of the energy resources at Lucingweni results in an optimal mix with least cost of 92 kW hydro power, 60 kW wind energy generator, 50 kW diesel generator, 150 kW converter and 200 kWh battery system. The renewable energy fraction is 99% with 81% of the electricity production coming from the hydro power, while 18% is from the 10 kW wind generator and about 1% is provided by the diesel generator (Fig. 4). The renewable energy fraction for the SHS is 100%.

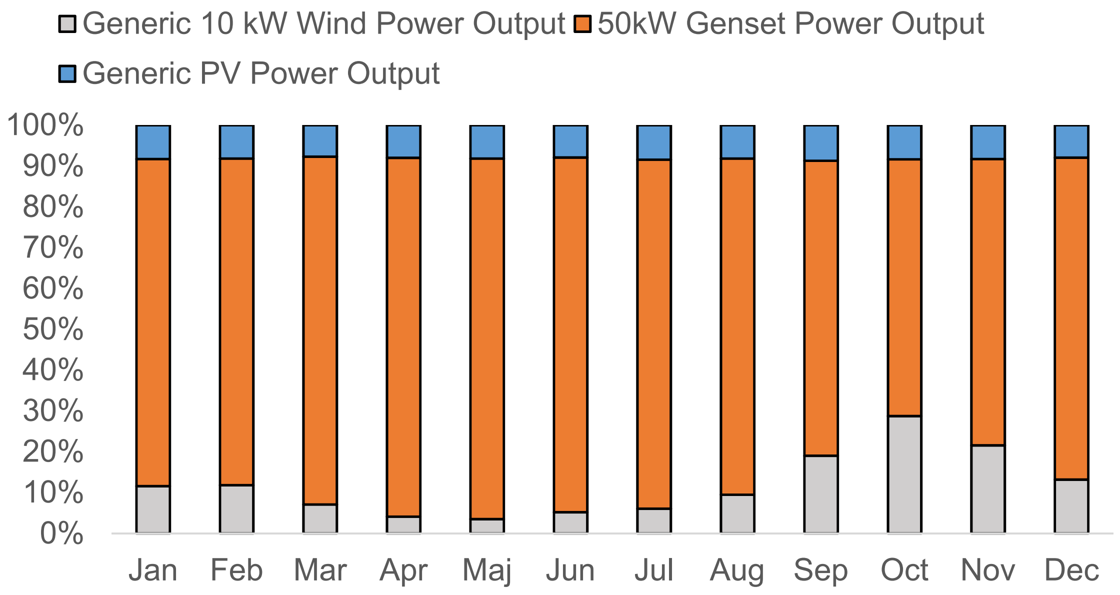


Figure 3: Energy mix for Thlatlaganya mini-grid project

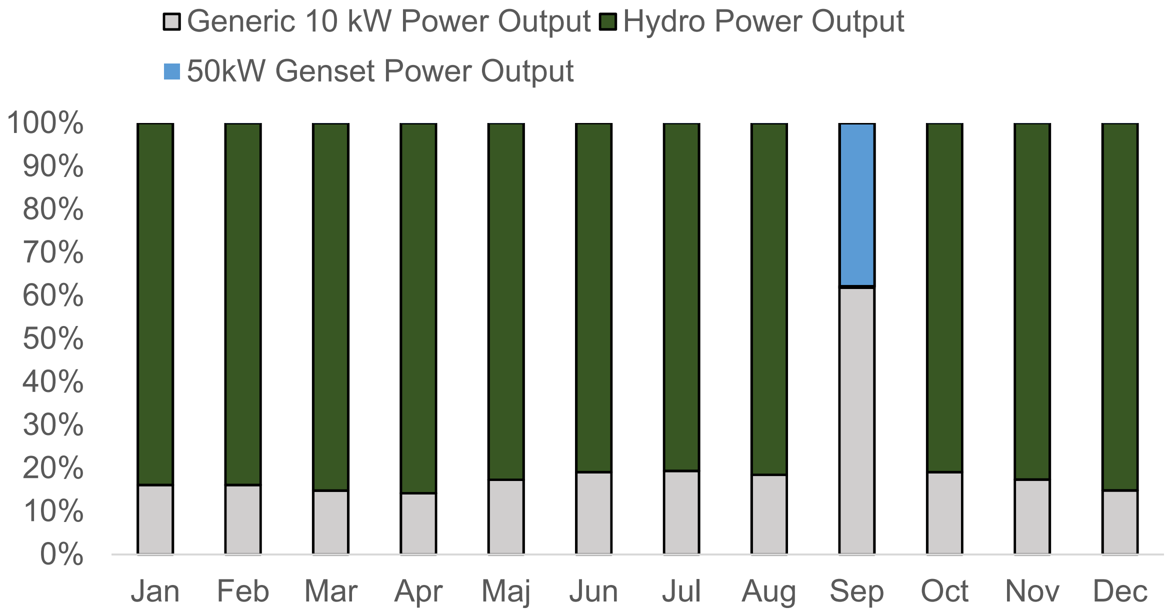


Fig. 4. Energy mix for Lucingweni mini-grid project

3.1.4 Electricity production capacity of the two mini-grids

The electricity produced by the two optimized mini-grid systems is able to meet the loads with excess production. Some of the excess electricity produced is used by the pumping machine as dump loads. This shows that the mini-grid systems are able to meet loads capable of supporting domestic, social and economic activities as designed, which is a precondition for the establishment of small and medium scale businesses. The simulation shows that there is around 75.6% excess electricity in the Lucingweni mini-grid, while there is around 2% excess in the Thlatlaganya mini-grid (Table 4).

Table 4: Electricity production profile of the two mini-grids

Location	production [kWh]	consumption [kWh]	Unmet load [kWh]	Excess electricity [kWh]
Thlatlaganya	291512	268929	0	5,560
Lucingweni	1169131	268855	0	883993

3.1.5 Assessment of power quality of mini-grid and solar home system using the state of charge of the battery

The results from the simulations show that there is less reliance on batteries in the mini-grid than in the SHS (Fig. 5). The SOC in the mini-grids show that Lucingweni and Thlatlaganya are able to achieve around 99% and 93% SOC respectively during operations. The occasional dips in the amplitude of the oscillations indicates occasions when the system is more reliant on batteries to meet the electricity demand. The noticeable dip indicated by the green line for the Lucingweni mini-grid is a result of the reduced flow of the Mbashe river during the month of September, when the average flow rate of 30.75 m^3/s drops to 2.02 m^3/s (see Fig. 1). At this period, the system relies more on the battery and the 50 kW generator to meet the shortfall in electricity generation resulting in excess electricity being drawn from the battery. The frequent rise and fall in the amplitude of oscillation in the SOC for the SHS indicated by the grey dotted lines shows that the battery is constantly under load (Fig. 5). The system constantly relies on the battery in order to meet the energy needs during operation. The SOC of the SHS achieved under these conditions is about 50%.

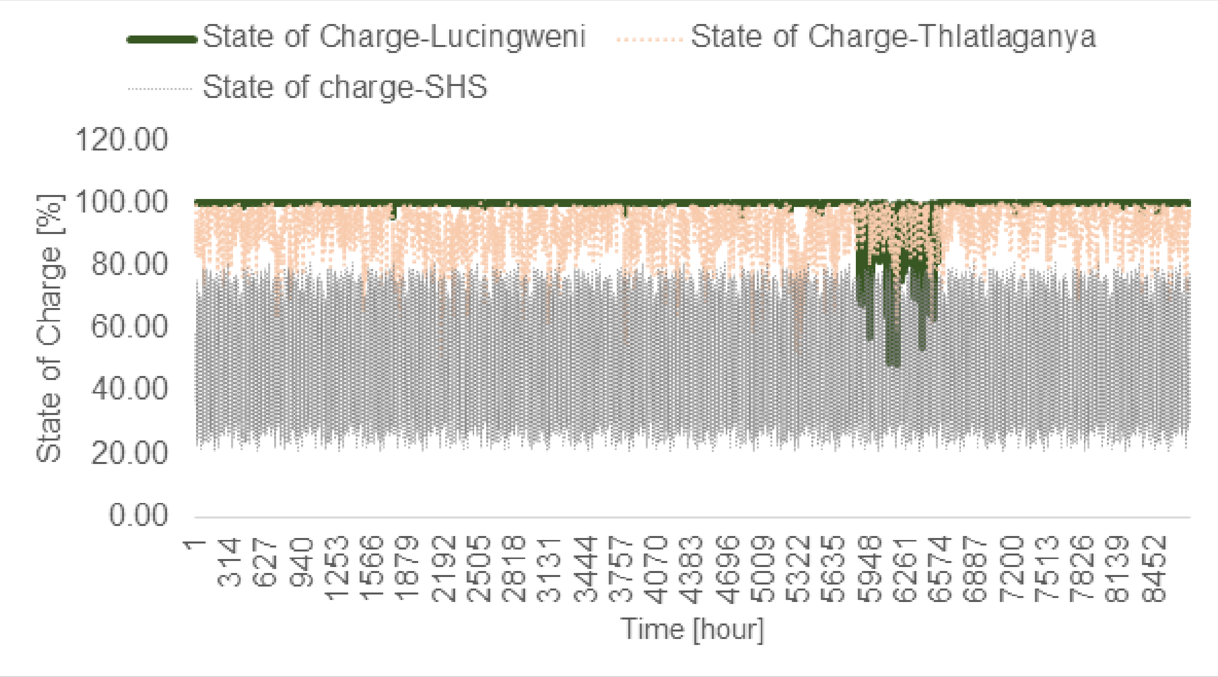


Fig. 5. State of charge of the battery in the mini-grids and Solar Home System

3.2 Economic evaluation of the mini-grids

The economic evaluation of the two mini-grids provides information on the cost of implementation and operation during the life cycle of the systems.

3.2.1 Economic analysis of the two mini-grids

The evaluation of the economics of the two mini-grids reveals that the LCOE is \$0.08/kWh for the Lucingweni mini-grid, and \$0.41/KWh for the Thlatlaganya mini-grid (Table 5). The LCOE for both sites is higher than the current cost of electricity from the national utility company Eskom, which is \$0.06/kWh [26]. Despite this the LCOE for the optimized system is lower than the actual LCOE obtained for the Lucingweni pilot mini-grid project. A previous study showed that the LCOE for the Lucingweni project had to be about \$0.14/KWh for the electricity production cost to be recovered. This situation contributed to the failure of the project [5].

Table 5: The economic analysis of the two mini-grid systems

Location	IC [\$]	LCOE [\$]	NPC [\$]	OC [\$]
Thlatlaganya	357,000	0.41	2,884,578	95,509
Lucingweni	240,000	0.08	558,018	12,017

3.2.2 Grid extension breakeven distance

According to HOMER™ the breakeven grid extension distance (BED) is defined as the distance at which the total NPC of the grid extension is equal to the total NPC of the stand-alone system. The results from HOMER™ simulations show that the BED is about 68 km for Thlatlaganya village. This means that extending the grid to Thlatlaganya makes economic sense if the distance from the grid is ≤ 68 km, beyond this distance the cost exceeds that of a standalone mini-grid (Fig. 6). The BED for the Lucingweni mini-grid obtained in this study is about 4 km (Fig. 7). However, during the implementation of the pilot mini-grid project the grid was about 17 km away from Lucingweni village, and it is currently about 11 km away. Nevertheless, the pilot mini-grid project was installed at a BED of about 21 km when it was implemented [5].

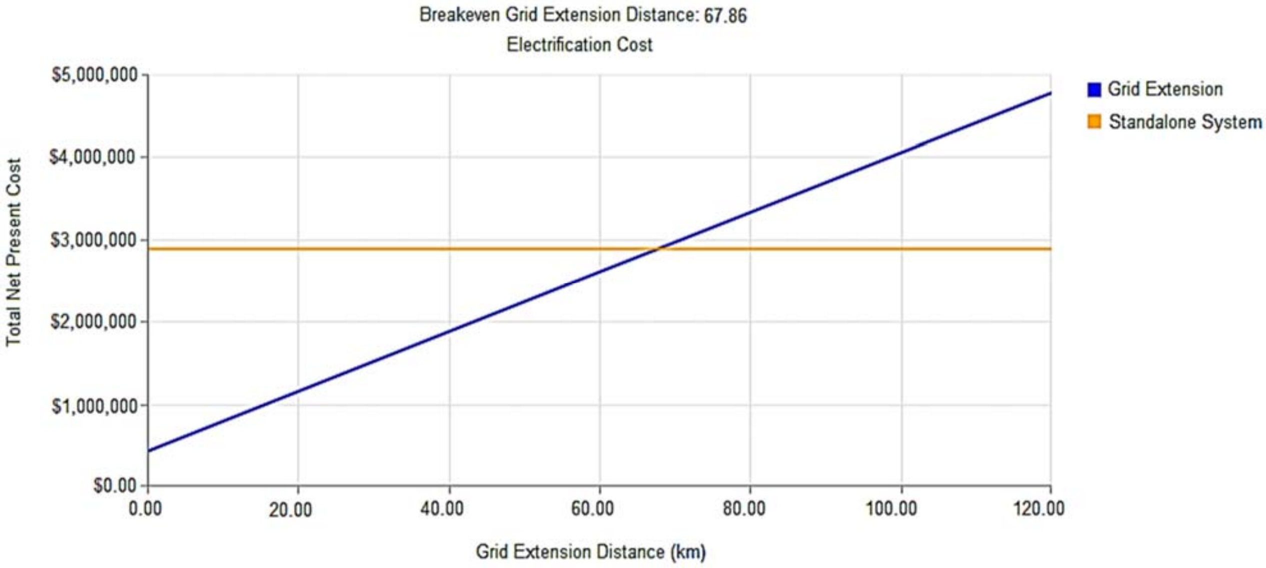


Fig. 6. Grid extension breakeven point for mini-grid in Thlatlaganya

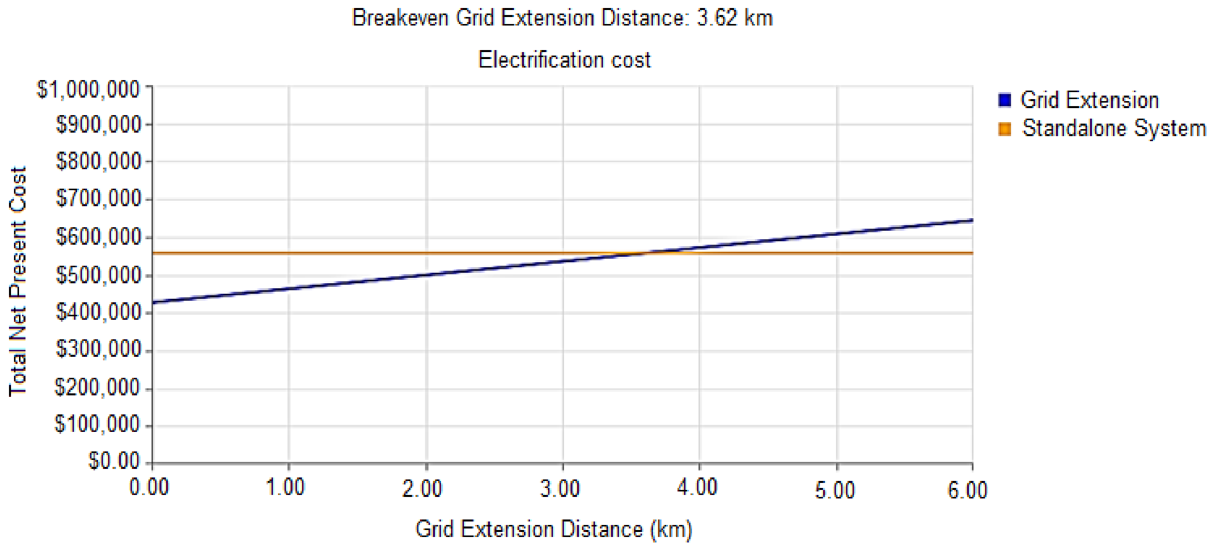


Fig. 7. Grid extension breakeven point for the mini-grid in Lucingweni

3.2.3 Fuel consumption profile for Thlatlaganya mini-grid

The total fuel consumption per year for the Thlatlaganya mini-grid is 72,640 L, and the average consumption per day is about 199.04 L. The box and whisker plot shows that the daily average fuel consumption is about 8.30 L and maximum consumption per day is about 16 L (Fig. 8). The average consumption rate is higher in the winter months from March to August.

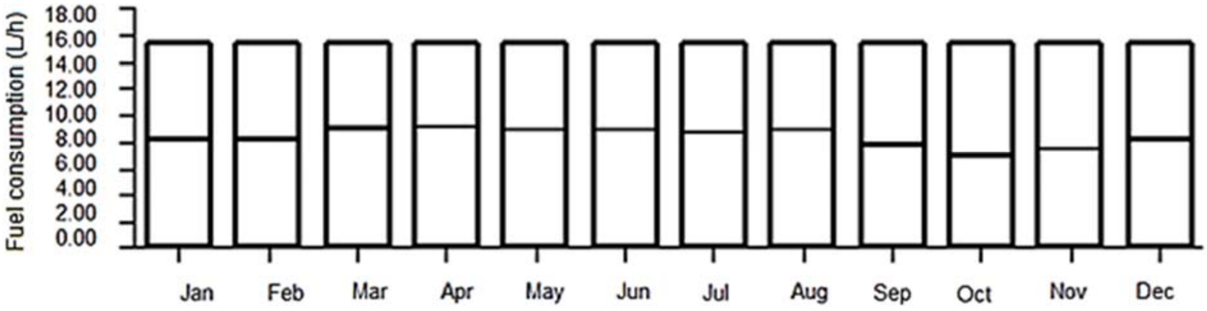


Fig. 8. The fuel consumption profile for the mini-grid in Thlatlaganya

3.2.4 Fuel consumption for Lucingweni Mini-grid.

The mini-grid in Lucingweni Mini-grid has an average fuel consumption per year of about 3,883.60 L, and the average daily consumption is about 10.64 L. The box and whisker plot indicates an average hourly monthly consumption rate of about 0.44 L. The maximum fuel consumption of 16 L occurs in September (Fig. 9). The average fuel consumption is low throughout the year, except in September when the flow rate of the Mbashe River falls from the average of 30.75 m^3/s to 2.02 m^3/s (Table 1), with a designed flow rate of 0.5 m^3/s, residual flow rate of 2 m^3/s and minimum flow ratio of 50%. The available flow (0.02m^3/s) in September is below the minimum allowable flow of the turbine (0.25m^3/s), and therefore the power output is zero at this time.

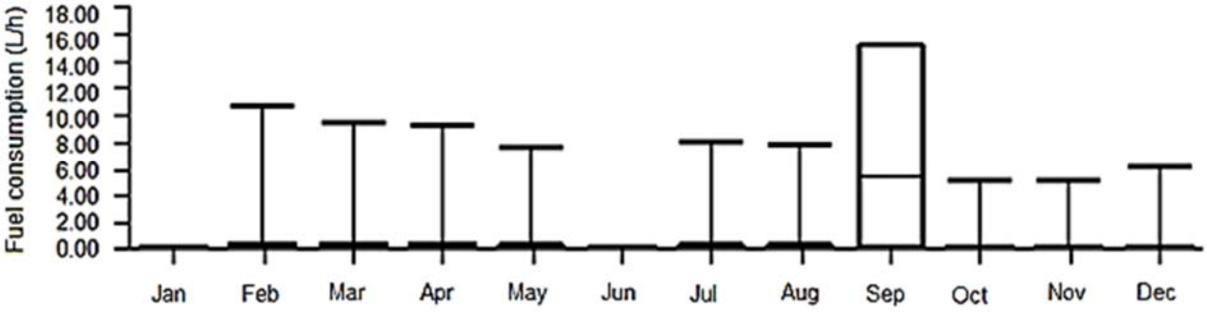


Fig. 9 The fuel consumption profile for Lucingweni Mini-grid

3.2.5 Impact of Wind speed variation on the technology and economics of mini-grids

Sensitivity analysis shows that the variation in wind speed has impacts on the mini-grid systems. The cost of fuel, OC and hours of operation decrease as the wind speed increases (Fig. 10). This is an indication that more energy is produced from the wind turbine, reducing the need to generate energy with the diesel generator. The increase in wind speed reduces the OC. BED and the LCOE. The simulation shows that when the wind speed is below 3 m/s, PV energy is needed in the Thlatlaganya mini-grid to meet the energy needs. When the wind speed increases to 4 m/s the system can operate without the need for PV in the energy mix. An increase in the wind speed to 4 m/s reduces the BED by about 17%, with a corresponding decrease of 11% in the diesel generator operating hours.

The same applies for the mini-grid in Lucingweni. When the average wind speed is below 4 m/s, it is not economically feasible to include the wind energy generator. When the average wind speed is above 4 m/s the BED is reduced by 39%. With the inclusion of the wind power source the operating hours of the 50 kW diesel generator (GEN50) are reduced by about 30%.

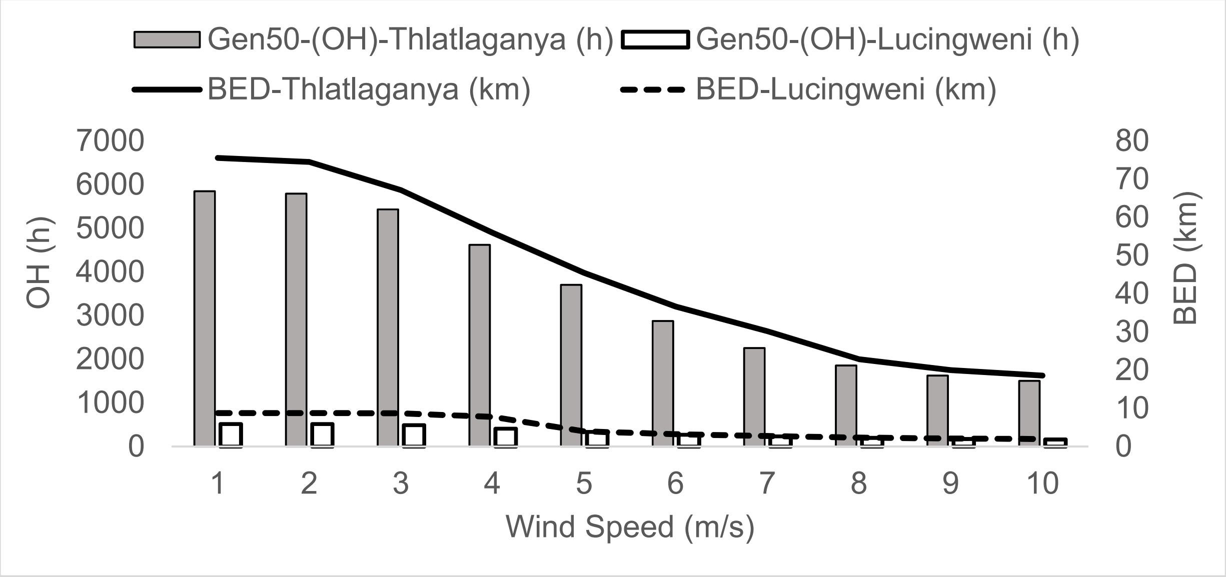


Fig. 10. Impact of wind speed variation on the generator operation and the breakeven grid extension distance

3.2.6 The impact of Variation of feedstock price on the economics of mini-grids

Increases in the diesel price increase the OH and BED for the Thlatlaganya mini-grid as indicated in the price sensitivity analysis (Fig. 11). The Lucingweni project is less affected by increasing diesel price as most of the load is met by hydro power, reducing reliance on the diesel generator. This results in fewer operating hours and reduced operation costs of the Lucingweni mini-grid, which has a significant effect on the BED. An increase in diesel price increases BED for both Thlatlaganya and Lucingweni mini-grids.

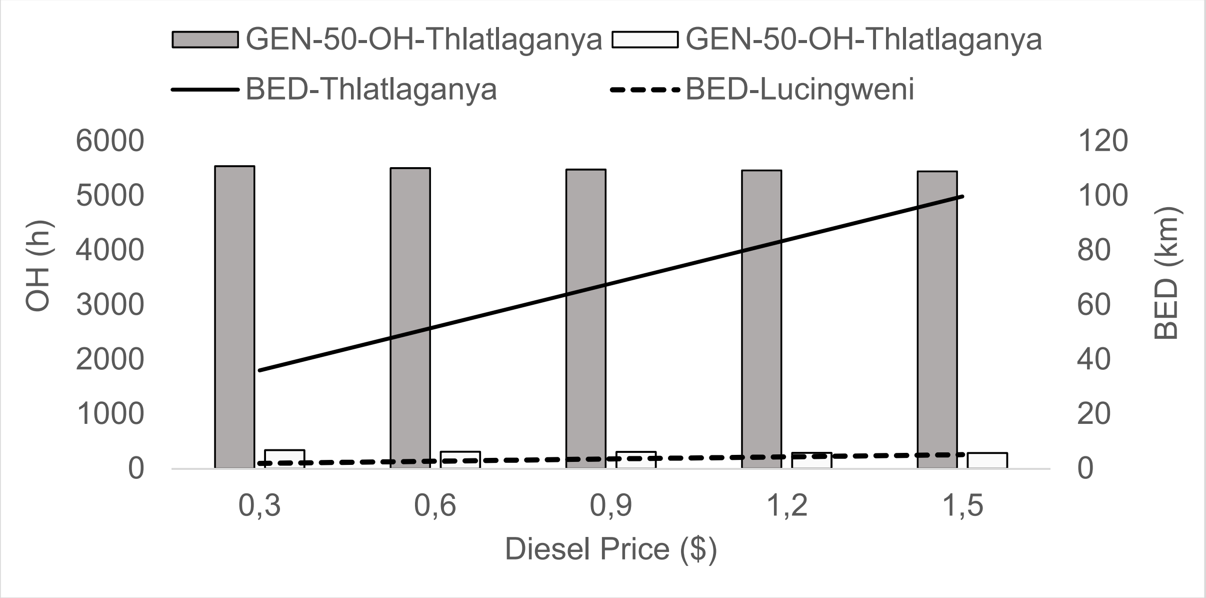


Fig 11: Sensitivity of diesel price variation on the breakeven distance and operation hours

4 Discussion

Solar radiation, wind speed and hydro resources are the most significant natural resources that influence the technology choices for the optimized mini-grid systems in both Thlatlaganya and Lucingweni. The reduction in solar radiation from April to September (i.e. in winter) results in an increased need for diesel and wind energy to meet the energy needs in Thlatlaganya. Similarly in Lucingweni, the reduced flow rate of the Mbashe River during the same period culminating in September results in the highest use of the diesel generator to meet the energy demand. This is in agreement with a previous study that concluded that a hydroelectricity system would require an additional source of electricity to meet the energy demand due to the reduced flow in the Mbashe River during the winter period [36]. Another study proposed that a combination of a hydrokinetic system and pump storage could complement the shortfall in electricity supply during seasonal variations of this nature [37].

The difference between the capacity of SHS and mini-grid systems is exemplified by their load profiles as illustrated in Fig. 2. The load profile of the SHS shows that the power capacity of the system is limited which explains the lack of productive activities during day. The actual situation may be more critical as the simulation stretches the capacity of the SHS to its limit to accommodate the load due to the behavioural pattern of the households, and this can only be met by overloading the system to provide 0.543 kWh/day/household [14]. This is evident from the noticeable stress on the SHS battery (Fig. 6). The SOC resulting from this usage pattern is 50%, reflecting the low power quality of the system. The optimization of the 75 W_P SHS used for the South African program shows that the system can only work optimally at 0.302 kWh/day/household [14]. Operating the system under optimized conditions increases the SOC to about 84%. However, this reduces the usage time as the system can only maintain an uninterrupted electricity supply under the optimal condition for about 3 hours [14].

On the other hand, the two mini-grids show that sufficient electricity can be produced to meet the load at a reduced price, indicating that the objective of supporting domestic and productive economic activities such as agriculture, commercial, and public utilities like schools and clinics, carpentry and metal works could be met with the electricity from the optimized mini-grids at the two sites. The 732 kWh required to meet the designed load excludes the technical losses resulting from battery storage, DC to AC conversion at the converter and electricity transmission and non-technical losses due to electricity pilferage as previously reported [17]. 24 hour availability of electricity will enable rural households to improve their income generation and payment for services. Improved income is likely to result in an increased demand for electricity, which is beneficial both for the energy providers and the households. This finding is in agreement with the argument that states that mini-grids have sufficient capacity to power small businesses which can spur the development of local economic activities and enable communities to improve their living conditions [38].

The investigation reveals that the inclusion of hydro power in the energy mix of the Lucingweni mini-grid gives it an advantage over the Thlatlaganya mini-grid in terms of high electricity production at reduced cost, even though Thlatlaganya has relatively high solar irradiation, low wind speed and no availability of nearby inland waterways suitable for hydro power generation. Hydro power is the most cost competitive electricity generation option currently available [39]. The mini-grid in Lucingweni does not favour the inclusion of PV as was done in the actual pilot mini-grid project. Although the average solar irradiation is high enough to favour the use of solar energy, the ambient temperature is also relatively high, and this has a negative effect on the energy production [40]. The addition of hydro power to the energy mix of the Lucingweni mini-grid results in excess electricity production due to the high flow rate in the upper Mbashe River (Table 1). Information from the HOMER™ simulation indicates that the system, records excess electricity in any time step in which electrical production exceeds the load and the excess cannot be fully absorbed by the deferrable load or stored by the battery bank. Excess electricity can be used by boilers (the designed mini-grid did not include boilers) or stored by batteries. HOMER™ ranks systems based on NPC, and it has no qualms about excess electricity. HOMER™ recognizes that there is no value to excess electricity, but it also recognizes the cost of avoiding it. HOMER™ was created to analyze this kind of tradeoff. Thus, even with a well-designed search space, HOMER™ sometimes chooses systems that produce excess electricity, and considers this an acceptable result.

The optimization of the two mini-grids shows a significant renewable energy contribution in the energy mix at Lucingweni, while in the case of Thlatlaganya the mini-grid relies to a large extent on diesel generators to meet the load, increasing the costs of electricity production.

The economic analysis shows that the mini-grid at Lucingweni will cost about three times as much as the implementation of the SHS, assuming that all the 300 households are provided with SHS at the rate of around ZAR 4,000 per installation [34]. The ICC will amount to $ 120,000.00 for all households using SHS in the village and the energy production from the mini-grid is more than five times higher than the total energy produced by the 300 SHS. This additional energy is required to drive economic and productive activities in the rural settlements.

The economic analysis also shows that despite the similarity in the initial capital expenditures (CAPEX) between the two mini-grids, there is a significant difference in their operational expenditures (OPEX) due to the fact that maintenance and operating costs are higher for the Thlatlaganya mini-grid compared to the Lucingweni mini-grid.

Sensitivity analysis of the mini-grids shows that a high diesel price contributes to high cost of OC, LCOE and NPC. It also shows that wind speed influences the choice of technology and variation in the price of diesel affects the economics and operational hours of the diesel generator. The investigation reveals that hydro power has high potential in implementation of mini-grids for rural electrification in remote areas, since it has the lowest cost, the lowest grid extension breakeven distance and provides excess electricity in relation to the energy needs. This result agrees with an earlier study that concluded that hydro powered village grids is the solution with the lowest generation costs and negative abatement costs [41].

The techno-economic analysis of the SHS and the mini-grid systems at the two sites shows that mini-grid electricity is able to meet energy needs and allow for an energy based economic development of the rural settlements. However, the economic viability of the mini-grid may be affected by its distance from the national grid. An earlier study concluded that long distance to the grid and environmental considerations make mini-grids a more acceptable option for remote rural settlements [42]. Given the multi-faceted challenges of rural settlements in developing countries, such as mountainous topographies, low energy demand, dispersed homesteads, the relatively low income of households, not all rural settlements are likely to be suitable for the establishment of mini-grid systems. Nevertheless, increasing concern regarding climate change and the rising cost of grid expansion encourages the need for the establishment of alternative energy systems like hybrid mini-grids based on renewable energy sources. According to [43], grid extension should be the final phase of a sequential rural electrification process.

5 Conclusion

The evaluation of technical and economic viability of the optimized hybrid mini-grids at two sites in South Africa show that a mini-grid is a better option than SHS for meeting the energy needs of rural communities in line with the development objective of the South African FBE policy. Key findings of the study are:

- The optimized mini-grid systems are able to produce enough electricity to allow for development activities like agriculture, businesses and public services in rural communities if the power is used appropriately.
- The study shows that with proper planning and the right energy mix, the levelized cost of electricity for the Lucingweni pilot mini-grid project could have been reduced.
- Locations in close proximity to inland waterways suitable for hydro power provide the most competitive and optimal conditions for mini-grids to meet the energy needs of rural settlements.
- There is no generic technology choice for mini-grid systems, locally available resources, and prices of feedstock and components determine the optimal technology and energy mix for each location.

5.1 Recommendations

From a techno-economic perspective the mini-grid is a viable alternative to the SHS in locations with access to suitable energy resources. However, sustainability of these initiatives requires cost recovery and sufficient financial and human resources to ensure continuous operation and maintenance of the systems, a research gap that is not addressed in this study.

To achieve its development objective the South African government needs to be pragmatic in the implementation of renewable energy policies. There is a need for the government to revise the current policy on the rural electrification program based on SHS to also include mini-grid solutions in areas with access to adequate resources.

Research is required on how to manage the OPEX phase of projects after commissioning, since this was the key failure point in the Lucingweni pilot mini-grid and a weak link in the sustainability of the Thlatlaganya SHS project.

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