An assessment of unforeseen losses resulting from inappropriate use of solar home systems in South Africa

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Abstract

One of the challenges to the sustainability of the solar home system (SHS) electrification program in South Africa is equipment theft. In response to this, communities susceptible to solar panel theft resort to mounting their panels flat on the ground so they can be looked after during the day and taken indoors at night for safe keeping. Other households use their security lights to illuminate their environment and provide security for pole and roof mounted solar panels at night. These actions have consequential effects on the performance of the SHS. Several studies have detected resentment from households regarding the low power quality from these systems. Most scientific contributions on the issue of low power from SHS have focused on the challenges based on the technical designs of the systems. The power losses due to the usage pattern of the system has not received much attention. This study therefore reports on the technical losses as a result of the deviation from the designed and installed specification of the system by the users in order to protect their systems. It also investigates the linkage between the technical and economic losses which affects the sustainability of SHS program. A case study was performed in Thlatlaganya Village within Limpopo province in South Africa. Technical analysis using PVSYST solar software revealed that the energy output and performance of the battery is compromised as a result of these practices. Economic analysis indicates that the battery life and the economics of owning and operating SHS are affected negatively. The study recommends solutions to mitigate these losses, and proposes a cost effective way of optimizing the operation of SHS using a bench-rack system for mounting solar panels.

Keywords: SHS performance optimization; Rural electrification sustainability; Life cycle cost; User education; Solar panel theft; Battery life expectancy.

1. Introduction

The increasing cost of grid expansion and the externalities associated with fossil energy production have made renewable energy systems (RES) an irresistible choice for rural electrification programs (REP) in many developing countries. Evaluation of factors essential for a robust rural electrification program in Bangladesh and Fiji indicates that photovoltaic (PV) solar systems represents the most cost effective means of providing electricity to remote rural households [1]. Analysis of rural electrification programs in many villages in Nepal revealed that there is no convincing alternative to solar PV systems [2]. A review of RES production and utilization in Thailand indicates that a combination of renewable energy sources like PV, wind and diesel generators has good potential for implementing decentralized electricity for remote rural communities [3]. The appraisal of economic viability of different energy sources for rural electrification in Vietnam showed that the levelized cost of PV energy is lower than the alternative from the fossil grid [4]. SHS electrification program has been found to be a useful tool in reducing rural-urban migration in remote villages in rural Romania [5].

Assessment of rural electrification programs in South Africa showed that SHS is the most common technology used to increase access to energy in the informal settlements due to its comparative advantage over other renewable energy sources [6]. The South African SHS program has been in place for more than a decade, resulting in many rural communities being equipped with solar based electricity systems [7]. However, the sustainability of the South African SHS program is under threat due to theft of solar panels and the resultant behavioural change of the households using the systems [8-10].

Theft of solar panels have resultant effects on the usage pattern of SHS as has been reported in numerous scientific publications. In India, an assessment of the Sundarbans project showed that most households have moved their solar panels from the optimal south facing position to more visible positions with less solar irradiation, to ensure that their equipment is not stolen [11]. In Papua New Guinea, equipment theft has compelled many households to return to solid fuels to meet their energy needs [9]. Panel robbery has become so common in rural Zimbabwe that most people now prefer to invest in other ventures, while some households have resorted to shielding their panels with steel bars, which causes shading of the panels [12]. Our investigation of South African experience with SHS theft revealed two emergent trends. One is the use of security lights to illuminate pole and roof mounted panels at night. The other is the habit of keeping solar panels under surveillance for 24 hours of the day by most households, by placing them flat on the ground in front of their houses during the day to keep them within sight. At night, the panels are taken indoors for safe keeping.

These twin practices have been reported to have significant effects on the performance of SHS as a result of non-optimal use of the systems. A study conducted in Tehran shows that snow, pollution and dust affects the performance of solar panels, and that these effects are more severe at small tilt angles [13]. Performance analysis of PV systems show that the optimal tilt angle in the southern hemisphere is close to the latitude (θ) of the location [14]. The energy output of PV systems has been found to improve by placing them at an optimal tilt angle of (θ-10) in summer, and (θ+10) in winter [15]. Operating a PV thermal collector with reflectors at optimal positions improved both the electrical and thermal energy generated [16].

The two adaptive behaviours that we found have attendant effects on the economics of the SHS program, given by the reports from various studies in this field. A field study on the performance of lead-acid batteries associated with domestic PV lighting systems in Mexico, found that inappropriate use and limited maintenance practices emanating from lack of user education resulted in shorter battery life [17]. A study in Lundazi, Zambia indicates that overloading systems beyond the designed specification has a negative effect on the technical life of the battery [18]. In addition [19] showed that short battery life and high cost of replacement motivates the use of cheap batteries.

These adaptive behaviours are thus likely to affect the sustainability of the SHS program due to increased cost resulting from replacement of batteries. Many studies on the economics of PV systems have shown that they have economic advantages over other RES and fossil grid energy sources for rural electrification programs. After analyzing the techno-economic feasibility of grid connected PV systems using life cycle cost (LCC) [20] concluded that PV costs can be reduced with subsidies and tax exemptions. An evaluation of LCC of PV systems used in electrifying remote rural households in India showed that it is beneficial and suitable for long-term investment [21]. LCC model was used to determine the optimum relation between PV array size and the battery capacity [22]. The environment impact of fuels used for cooking in Ghana was investigated using conventional life cycle costing method [23]. Similarly, the influence of geographical location and the PV type on environment load and energy payback time (EPT) was evaluated using LCC [24]. An optimal sizing method based on genetic algorithm was used to achieve a required loss of load probability (LOLP) at a minimum annual life cycle cost (ALCC) [25].

The measures adopted by locals to protect their SHS are a reflection of lack of user education amongst the households in communities vulnerable to SHS theft in South Africa. Lack of user education is an indication of the alienation of the locals from projects. Following the assessment of lessons and experiences of rural electrification programs in Africa, [26] argued that SHS is a useful tool for rural development and electrification, but large scale diffusion of it demands an energy policy that supports partnership with local inhabitants. After analyzing 232 scientific articles, [27] recommended post-project plans that outlive subsidies in order to increase the likelihood of self-sufficiency and long term viability of projects in rural communities. Previous study have reported that a well articulate public-private partnership can deliver a cost effective energy service in rural areas [28]. The importance of partnering with the locals in rural electrification programs cannot be overemphasized, this situation captures the argument of [29] when it posits that, rural electrification programs can benefit greatly from the involvement of local communities or suffer because of its absence.

Reports from many scholarly article indicates that the low power capacity of SHS is a major challenge, and a veritable source of resentment against the system by the locals [30-32]. Publications such as [33] advocates for an increase in the capacity of SHS in order to improve the limited power capacity of the system. The use of sophisticated controllers to enhance performance of SHS has been achieved in a study like [34]. Bypassed diodes has been used to mitigate the effect of shading, thereby maintaining the power quality of a shaded solar panels [35]. Most of these solutions concentrated on the technical design of solar panels and its paraphernalia. Meanwhile, little attention has been given to the power losses that occurs on daily basis as a result of the usage pattern of the equipment. This study therefore investigates the technical and economic losses resulting from the divergence between the designed and the usage pattern of SHS in selected rural settlements in South Africa. It investigates the linkage between the technical losses and the resultant economic losses following the behavioural change of the users in response to solar panel theft. In addition, it recommends the right size of load suitable for the capacity of SHS currently in use in South Africa. Furthermore, it uses PVSYST solar software to investigate the right size of SHS that will meet the energy need of users in line with the adopted practices, and proposes a cost effective Bench Rack solar panel mounting device[1] for the optimization of operation of SHSs in developing countries.

2. The standard Solar Home System used in South Africa

The SHS used for the South African rural electrification project is a direct current (DC) system. It consists of a solar panel (either $50W_P$ or $75\ W_P$), a 100 Ah, 12 V battery pack, battery safety fuse, and a charge controller. Electricity generation is achieved using solar panels, the battery stores the energy during the day and provides energy to the household load when the solar panel is not generating at night. The control unit controls the charging of the battery and provides a low voltage disconnect function against excess discharge of energy from the battery. Because the output power is low, it is used for appliances with low power consumption such as, lighting, DC television, radio, and cell phone charging (Fig 1). The performance of the SHS is compromised when it is overloaded, which occurs when loads are used for extended periods or when oversized loads are connected to the system. The performance is also affected when the charge controller is bypassed. The charge controller is bypassed by connecting the load directly to the battery. Information from several SHS energy services providers confirm that this is a common practice by

1. [1]The Bench-Rack solar mounting system is designed to assist the poor households to achieve optimal use of solar home systems in the most cost effective manner. This is intended to overcome the habits of placing solar panels flat on the ground and the use of lights at nights to provide security for pole and roof mounted panels as a result of theft of solar panels.

uninformed users to allow access to electricity from the battery, after the low voltage-disconnect function of the control unit has disconnected them from the supply. Other factors that compromise the performance of SHS include shading from obstructing objects, animal and bird droppings etc. This scenario represents a typical example of the challenges faced by SHS operators in South Africa.

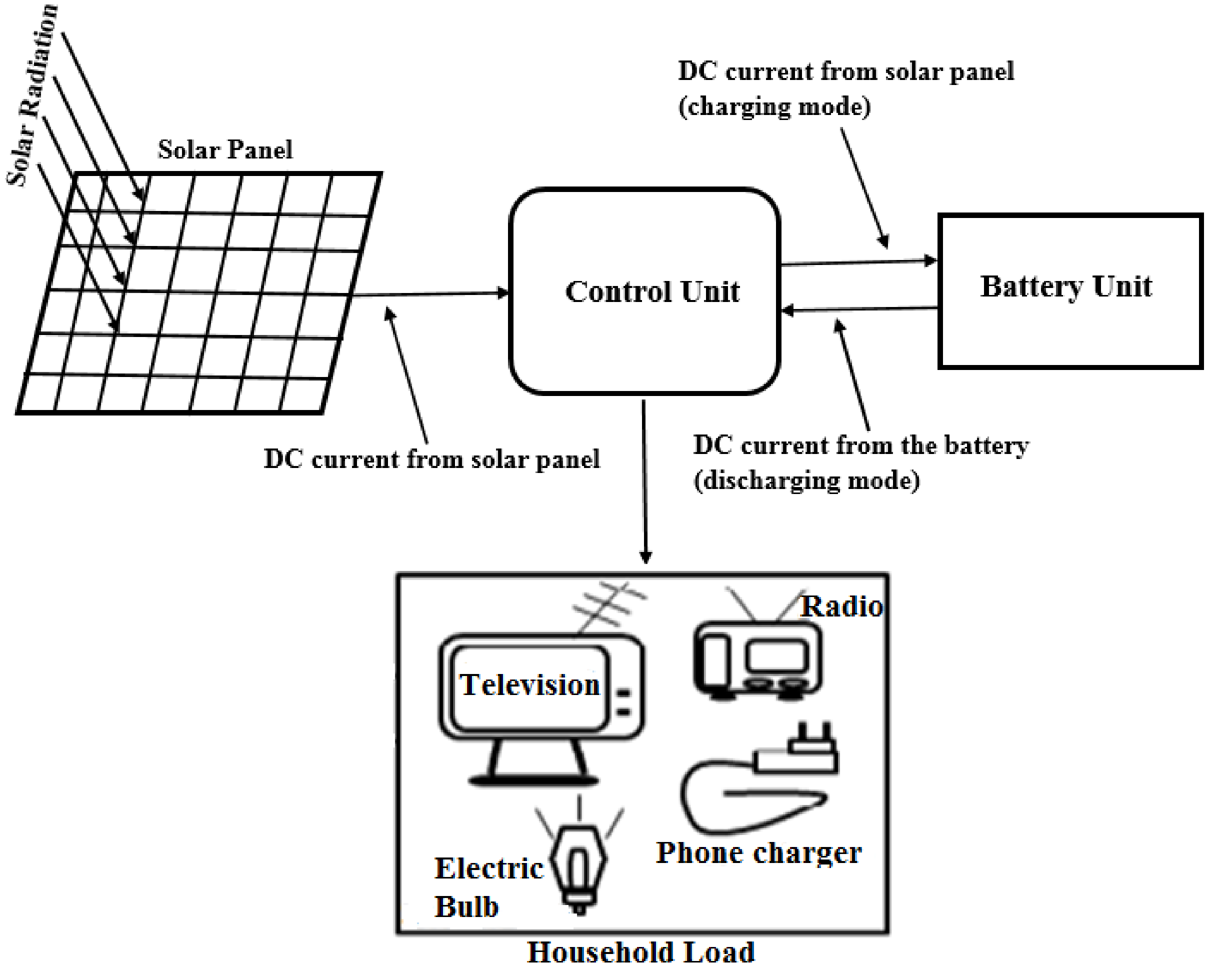

Fig.1. Configuration of solar home system for rural electrification in South Africa

3. Methodology

Data on the SHS usage pattern of households were obtained through semi-structured interviews with 88 SHS-using households in Polokwane, greater Tubatse and Vhembe municipalities in Limpopo province (Solar Vision concession area) and uMkhanyakude district municipality in northern Kwazulu Natal province (NuRa Energy concession area). Interviews were held with the management of Kwazulu Energy Services

(KES) Company (southern Kwazulu-Natal and Eastern Cape Province concession areas). The relevant staff of the Department of Energy (DOE), the Department of Rural Development and Land Reforms (DRDLR), and the managers of the three energy service providers known as the concession companies (represented by Solar Vision, NuRa Energy and KES) were also interviewed. This was done to obtain information on their experiences, in terms of usage patterns, challenges and opportunities associated with the SHS program.

We subjected the data obtained during the survey to a scientific analysis using PVSYST solar energy software in order to verify the claims of some of our respondents. This is necessary to understand in scientific terms and to place in proper perspective the challenges faced by households using SHSs in developing countries as a result of limited knowledge of the system.

3.1 Technical analysis

Based on information gathered during the survey, the household load for the standard system was modeled on the current pattern of energy usage in Thlatlaganya village in Polokwane Municipality in Limpopo province. The optimized system was achieved by first obtaining the optimum tilt angle (β) for Polokwane municipality through simulation and then calculating the seasonal tilt angles using the equation (θ-10) for summer and (θ+10) for winter in accordance with [15]. The load profile for the optimized system was obtained through reduction of the household load in steps, until there was no mismatch between the energy need and energy supply, while the solar panel was simulated at the optimized seasonal tilt. The load was reduced to meet an optimal size in line with the capacity of the SHS. The overloaded system was simulated by leaving two 9 watt outdoor lights on for extended periods, simulating the practice of many users in the village. The optimal tilt angle was used for the simulations in the overloaded system, since the solar panels are mounted on poles and roof tops in line with designed specification. The loads obtained were used to determine the state of charge (SOC) and depth of discharge (DOD) of the battery as given in equation (1).

$$DOD = 1 - SOC \quad (1)$$

The loss of load probability (LOLP) for the three systems was simulated using values obtained from the load balance and battery performance analysis. The battery life expectancy was calculated using equation (2) according to [36].

$$Bat_{lifecycle} = (89.59 - 194.29T) * e^{(-1.75*DOD)} \quad (2)$$

The specification of the SHS used for the simulation is a $75\,W_p$ solar panel and a 100 Ah, 12V battery unit (A deep cycle lead-acid battery is used for this investigation), which is the same specification as the SHS currently used for the rural electrification program in South Africa. Although the surveys and interviews were conducted in three provinces, the location used for the simulation was Thlatlaganya village in Polokwane municipality in Limpopo province. In the study, Meteonorm weather software [37] was used to obtain the weather information of Polokwane municipality. Polokwane is located at latitude -23.87°S and longitude 29.45°E. The optimal tilt angle for Thlatlaganya village was determined using TRNSYS-Winsun solar energy software [38] under the fixed tilt geometry system. PV.SYST solar energy software [39] was used to investigate the SOC of the battery using the load profile for each system. The simulation was carried out with 5% loss of load (LOL) factor and the battery days of autonomy was set at 3. Three case studies were carried out: Case 1 focuses on obtaining the optimal tilt angle, the energy output of the system at 0°, the optimal and seasonal tilt angles. Case 2 focused on the SOCs for the standard, optimized and overloaded system: and Case 3 investigated the LOLP for the three systems. The economic analysis was performed using financial instruments such as, the LCC, annualized life cycle cost (ALCC), and unit cost of electricity (UCE) as indicators.

3.2 Economic analysis

The LCC for SHS is calculated without taking into consideration the inverter, since the analyzed SHS is a DC system. Therefore, in this case the LCC is given by equation (3) [20, 40, 41]

$$LCC_{SHS} = C_{SOLP} + C_{CC} + C_{INST} + PW_{CM} + PW_{Bat} - SPW_{Bat} \quad (3)$$

The total cost of SHS is calculated using equation (4)

$$C_{SHS} = C_{SOLP} + C_{CC} + C_{Bat} \quad (4)$$

Where,

C_{SOLP} is the cost of solar panel, C_{CC} is the cost of the charge controller, while C_{INST} is the cost of installation of SHS, PW_{CM} is the present worth cost of maintenance of SHS throughout the life cycle, PW_{Bat} comprises the initial cost of battery and present worth of additional batteries, SPW_{Bat} is the salvage value of the battery at the end of the projected life span, and C_{SHS} Is the total initial cost of SHS.

$$PW_{Bat} = C_{Bat}(x)^0 + C_{Bat}(x)^1 + C_{Bat}(x)^2 .... + C_{Bat}(x)^{n-1} \quad (5)$$

Where $x = \frac{1+i}{1+d}$, and C_{Bat} = the initial cost of battery.

The salvage value of the battery is calculated using equation (6) [40].

$$SPW_{Bat} = C_{Bat}(Bat_{\mathrm{Re}mlife} / Bat_{lifecycle}) \quad (6)$$

Where, $Bat_{\mathrm{Re}mlife}$ represents the remaining lifetime of the Battery at the end of the estimated life cycle (25 years).

The present worth cost of maintenance of the battery is given by equation (7) [21][42].

$$C_{PWCM} = (C_{M/Y})(x)\left\{\frac{1-(x)^N}{1-(x)}\right\} \quad (7)$$

Where, $(C_{M/Y})$ is the maintenance cost per year, and $\left\{\frac{1-(x)^N}{1-(x)}\right\}$ is the cumulative present worth factor (PW_{CF}), and N is the estimated lifetime of the SHS (20 years).

3.2.1 Annualized life cycle cost (ALCC) and Unit cost of electricity

The value of $ALCC_{SHS}$ is obtained by dividing LCC_{SHS} with the cumulative present worth factor [41].

$$ALCC_{SHS} = LCC\left\{\frac{1-x}{1-x^N}\right\} \quad (8)$$

The unit cost of electricity is obtained by dividing the $ALCC_{SHS}$ by the kWh (load) [41].

Therefore,

$$UCE_{SHS} = \frac{ALCC_{SHS}}{E-User(kWh/year)} \quad (9)$$

3.2.2 Analysis of LCC, ALCC and UCE for the standard, optimized and overloaded system

The analysis of LCC involves knowledge of the battery life (since the battery is the most replaceable component of the SHS), the average SOC and DOD of the system. The cost data for this analysis were derived from Table 1.

Table 1: Cost analysis for SHS components

Item	Cost
Solar panel	\$5/W[43, 44]
Battery	\$3.6/Ah [45]
Current (I_{SC})	4.8 Amp [39]
Charge controller	\$6.2/A [46]
Installation	10% of SHS cost [21, 47]
Maintenance/Operation/Year	2% of SHS cost [21, 47]
Bench-Rack	\$22.2 at foreign exchange of 9.0 ZAR/\$1.0)

3.2.3 Assumptions made for the calculations

The life time of the SHS components except the battery is assumed to be 25 years [44]: There is no inverter cost: The cost of maintenance is 2 % of investment cost [21]: The inflation rate (i) is 3%, and the discount rate (d) is 10% [21, 41]: A temperature (T) constant of 25°C is used for the battery [48]: Only the battery needs replacement during the assumed lifetime of SHS.

4. Results

This section starts with investigation of the optimal tilt for Thlatlaganya village in Polokwane municipality in Limpopo province of South Africa. The optimal tilt occurred at the highest energy output of the system. This is followed by LOLP which indicates the extent of reliability of power and the effect of reduced power generation and overload on the battery system as indicated by the SOC. The section is concluded with the presentation of the result of economic analysis.

4.1 Technical analysis

In the technical analysis the results of the optimal tilt, seasonal tilt angles, energy output of SHS, daily load demand for the standard, optimized and overloaded systems, the LOLP, the estimated life expectancy of the battery, and the SOCs of the systems are presented in this subsection.

4.1.1 Optimal tilt angle for Thlatlaganya village

The study of the optimal tilt angle using the fixed tilt plane geometry for SHS operating in Thlatlaganya Village in Polokwane indicates that the highest energy output occurred at 24° tilt as represented in Fig. 2. A SHS system operating in this locality in the southern hemisphere will operate optimally at 24° tilt towards north. The optimal tilt (β) angle obtained in this investigation is almost the same as the latitude ($\theta = 23.87°$) of Polokwane municipality. Therefore, 24° is used as an approximation for the latitude in this study to simplify calculations.

Fixed tilt geometry is normally employed for SHS operation due to its simplicity and cost justification. Tracking geometries such as two axis tracking, North-South tracking and vertical axis tracking etc., have been found to improve power output of solar panels. However, due to their technical complexity and overhead costs, the fixed tilt system is the preferred option for low income rural households.

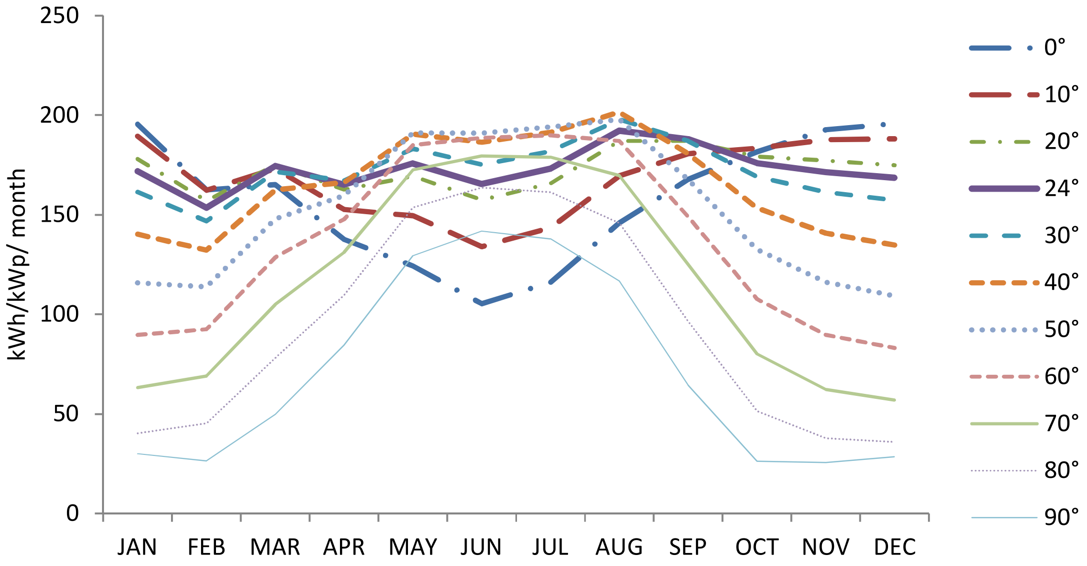

Fig.2. PV power output at different tilts angles

4.1.2 PV energy output at 0°, 24° and 14°/34° tilt

Three different fixed tilt positions were used to investigate the effect of tilt angle on the energy output of SHSs for Polokwane municipality, the fixed tilted plane at 0°: the optimal tilt at 24°: and seasonal tilts at 14° for summer and 34° for winter. The results show the global irradiation, the beam irradiation and the PV-module energy output at different angles of tilt. The performance of the PV module indicates that the highest energy output occurs at 24° tilt for the fixed system as shown in Table 2. The fixed tilt non-tracking system provided an energy output of 1891 kWh/kW$_P$/year at 0° tilt angle. At 24° tilt the energy output is 2076 kWh/kW$_P$/year, and at the seasonal tilt (14° for summer and 34° for winter) the energy output is 2147 kWh/kW$_P$/year. There is therefore 1.10 gain representing 10% increase in the PV energy output at 24° compared to the horizontal position, at seasonal tilt the gain increased further to 1.14 (14%) as shown in Table 2. This is an improvement of 4% over the 24° tilt system.

Table 2: Solar panel performance result for different geometries

Tracking Geometry	Beam Irradiation (kWh/m2/year)	Global Irradiation (kWh/m2/year)	PV-Energy (kWh/kW_P/year)	Energy Gained
Fixed tilt at 0^0	1445	2127	1891	1
Fixed tilt at 24^0	1597	2295	2076	1.1
Seasonal tilt at 14°/34°	1640	2359	2147	1.14

The daily load demand and the optimal angle achieved in the investigation are shown in Table 3. This data formed the basis of the economic analysis in the following section.

Responses from the households interviewed during the survey indicate that the standard practice in communities affected by solar panel theft is to dismount the solar panels from roofs and poles and place them on the ground at 0° tilt. Lights are used for 5 hours per day, TV is used for 5 hours per day, and other domestic appliances like cell phone chargers and radio are used for a combined 8 hours per day. The kWh/day figure is obtained by multiplying the usage hours by the load-units. The daily energy demand for the standard system is thus 0.543 kWh/day as shown in Table 3: Optimizing the system revealed that, the capacity of the installed SHS can only support power for 3 hours of lighting, 3 hours of TV, and a combined 4 hours of radio and cell phones charging, making the daily energy demand is 0.302 kWh/day. When the lights were used for extended periods in the overloaded system, the daily demand increased to 1.022 kWh/day.

Table 3: The daily energy demand and the tilt angles for the three systems

	Standard system	Optimized system	Overloaded system
Light usage (hour)	5	3	17
TV usage (hour)	5	3	5
Radio and Phone (hour)	8.2	4	10
Tilt angle (degree)	0°	14°/34°	0°
Load (kWh/day)	0.543	0.302	1.022

The power rating for CFL bulbs in use is 9 W and the number of units is 4, the DC-TV is 30 W and the number of units is 1, the Radio and the Phone chargers cumulatively is rated 26 W, representing 20 W for 1 radio unit and 3W each for the 2 phone chargers per household.

However, PVSYST solar software recommends that to operate the SHS under the standard condition and overloaded condition the size of the SHS needs to be increased as shown in Table 4.

Table 4: PVSYST Optimization specifications for the standard, optimized and overloaded systems

Systems	Panel size (W_P)	Battery size(Ah)	Battery Voltage (V)	Load (kWh)
Standard	114	150	12	0.543
Optimized	75	100	12	0.302
Overloaded	214	283	12	1.022

4.2 Loss of load probability

4.2.1 Reduction of the LOLP for optimized system at 0°tilt with 14°/34° tilts

LOLP is used to indicate the possibility of power outages as a result of inadequate supply of energy by the SHS. In the optimized system, the energy supply balances the energy demand, i.e. both the energy demand and supply are 110 kWh/year. This is represented by E-Load (energy need of the household) and E-User (energy available to the household). During the seasonal tilt the LOLP is 0%, as shown in Table 5, but at 0° tilt the LOLP increases to 7.5% as shown in Fig. 3. The energy delivered to the load under this condition decreases to 102 kWh/year. The LOLP suggests that under this condition outages may occur for 657 hours out of the 8760 hours of the year.

Table 5: Load balance and battery performance of the systems

	Standard system	Optimized system	Overloaded system
E-Load (kWh/year)	198.27	110.23	373.03
E-User (kWh/year)	105.44	110.23	99.72
E-Miss (kWh/year)	92.83	0	273.31
LOL probability (%)	46.6	0	70.5

E-Load is the energy need of the user, E-User is the energy supplied to the user and E-Miss is the energy mismatch between the need and supply.

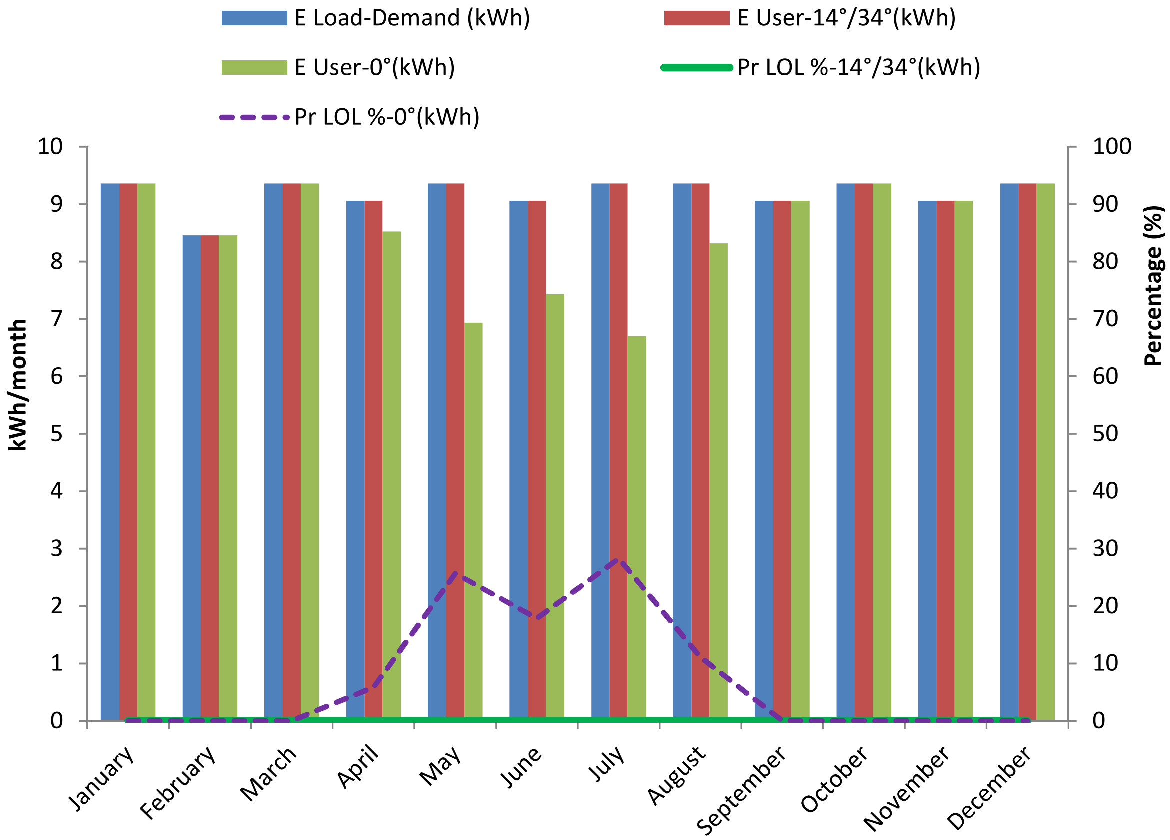

Fig. 3. The impact of seasonal tilt on LOLP of the optimized system at 0° tilt

4.2.2 Reduction of the LOLP of the standard system at 0° with 14°/34° tilts

LOLP for the standard system at 0° tilt is 46.6%, indicated by the dotted purple line in Fig.5. Operating the system according to the standard practice demands 198 kWh/year of energy from the system, but the system is able to supplied 105 kWh/year of energy. Under this condition there is an energy deficit for 4081 hours out of 8760 hours in a year. When tilted at 14°/34° (green line Fig. 4), there is an increase in the supply to 120 kWh/year, and outage hours are reduced to 3434 hours at a LOLP of 39.2%, representing 7.4% increase on the ability of the system to withstand the load.

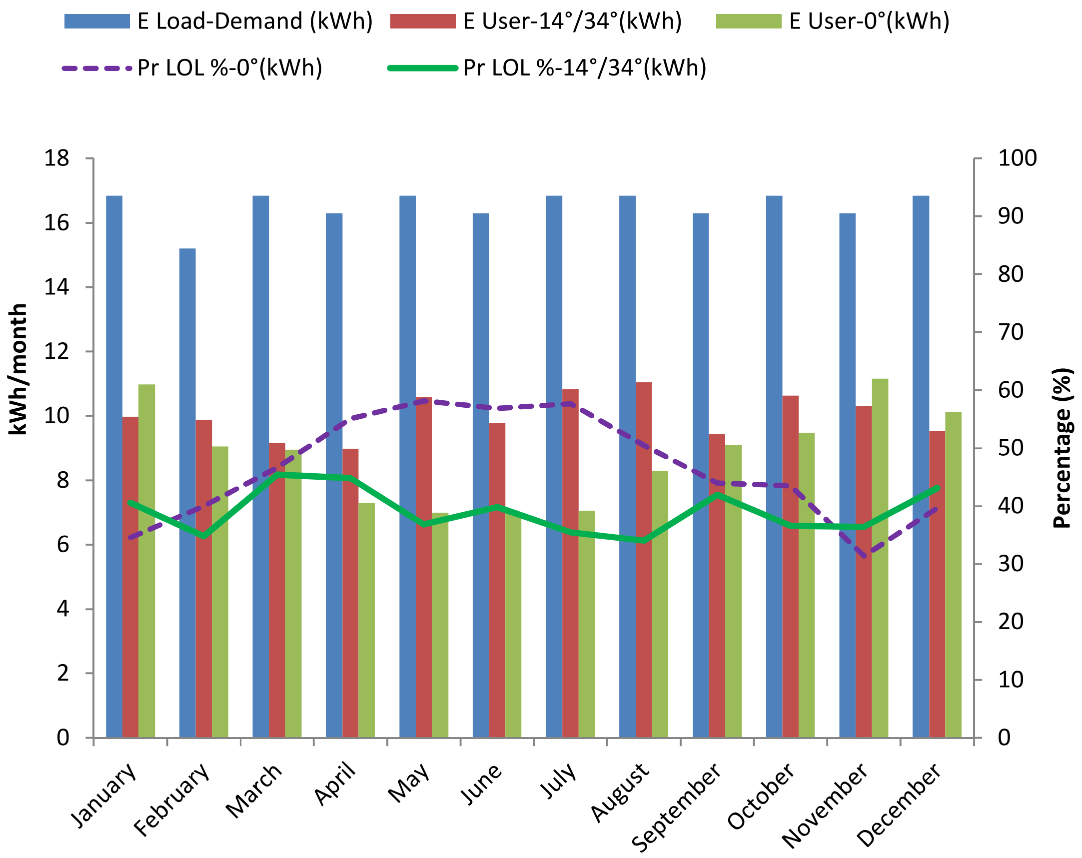

Fig. 4. The impact of seasonal tilt on LOLP for the standard system at 0° tilt

4.2.3 Reduction of the LOLP of overloaded system at 24° with 14°/34° tilts

The overloaded system showed a reduced ability to meet the load. The LOLP rose to an average of 70.5% when tilted at 24°, as indicated by the yellow line in Fig. 5, and 69.2% when tilted at 14°/34°, representing 1.3% increase, as shown by the green line in Fig. 5. Expected outage under these conditions is 6176 hours at 24° tilt and 6062 hours at 14°/34° tilt, out of 8760 hours in a year. 373 kWh/year of energy is demanded from the system in both cases. Using 24° tilt about 100 kWh/year of energy is supplied to the load, and at 14°/34° tilt 108 kWh/year is supplied. The small reduction in LOLP shows the inability of the seasonal tilt to reduce loss of load on the overloaded system. This indicates that the system is overstretched beyond the limit of its capabilities.

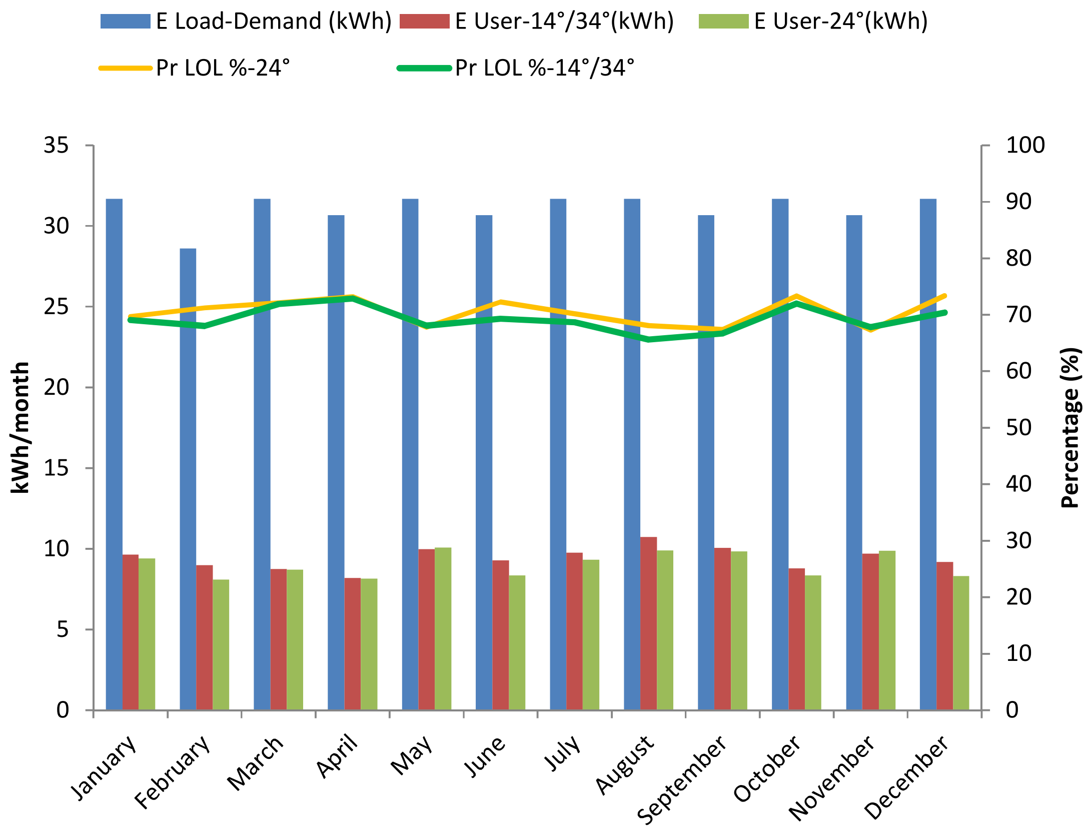

Fig. 5 The impact of seasonal tilt on LOLP of overloaded system at 24° tilt

4.3 The impact of non-optimal tilt and overload of SHS on the SOC of the battery System

In this section the result of the effect of reduction of energy input and the overload of SHS on the battery unit is presented.

4.3.1 Comparison of the SOCs of optimized, standard and overloaded systems

The investigation of the SOC for the optimized system indicates that the average SOC for the system is 86% giving a DOD of 14 %, indicated by the green line in Fig. 6. The SOC for the overloaded system is 48% and the DOD is 52 %, shown by the yellow line in Fig. 6. The average SOC of the standard system is 50 % and the DOD is also 50 %, as shown by the purple dotted line in Fig. 6. The low voltage disconnect function of the control unit disconnects the supply at about 25% SOC interrupting the discharge process until the battery charge reaches 75 % SOC, when the battery is reconnected to the load. This process determines the frequency of the oscillations in Fig.7. It takes about 2-3 days for the charging of the battery to reach this threshold (personal communication with Solar Vision technicians). The high frequency and the reduced amplitude of oscillations seen in both the standard and the overloaded systems indicate that the battery system is under stress. This effect is most evident in the overloaded system. The load in both cases is above the capacity of the battery, and more energy is needed to meet the load. Operating the SHS under this condition will have a negative effect on the performance of the battery.

Fig. 6 SOC for the optimized, standard and the overloaded systems

4.3.2 Estimation of the life expectancy of the battery

The estimated battery lives for the three system loads were calculated using equation (2) above. Under the standard and overloaded conditions, the expected battery life is approximately 6 years and 5 years respectively. Under the optimized condition the expected battery life increases two fold to 10 years approximately (see Table 6).

Table 6: The SOC, DOD and the battery life expectancy for the investigated systems

System	SOC (%)	DOD (%)	$Bat_{lifecycle}$(year)	No of replacements	$Bat_{Remlife}$(year)
Standard	50	50	6	4	1
Overloaded	48	52	5	4	0
Optimized	86	14	10	2	5

4.4 Economic Analysis

Using the component's costs information from Table 1 the C_{SOLP}, C_{Bat} and C_{CC} for a SHS with (75 W_P, 100 Ah and 12V battery) configuration is calculated to be \$375, \$360 and \$29.76 respectively. Substituting these values in equation 4 and 7, C_{SHS} and PW_{CM} is calculated to be \$764.76 and \$15.30 respectively. The economic analysis of the three systems shows that the LCC of the SHS is reduced significantly with the optimization of the system, as shown in Table 7. The LCC is reduced from \$1699.44 and \$1551.66 for the overloaded and standard systems respectively to $1257.72 for the optimized system, representing 26% and 19% reductions respectively. The UCE is also reduced from $1.16/kWh and $1.34/kWh respectively for the standard and overloaded systems to $0.90/kWh for the optimized system. This represents a reduction of 22% and 33% from the standard and overloaded systems respectively. The ALCC is also reduced from $122.27 and $134.03 for the standard and overloaded systems to $99.19 for the optimized system, representing a reduction of 19% and 26% respectively.

Table 7: Results of the economic analysis showing the LCC, ALCC and UCE

System	LCC ($)	ALCC ($)	UCE ($/kWh)	SPW_{Bat} ($)
Standard	1551.66	122.37	1.16	61.91
Overloaded	1699.44	134.03	1.34	0
Optimized	1257.72	99.19	0.90	48.32

5. Discussion

The findings presented here showed that the optimal tilt angle for a SHS operating in Thlatlaganya village according to the energy output is 24°. This supports the argument of [14] that optimal tilt angles at locations in the southern hemisphere are close to their latitude. The results also show that there is a gain of 10 % in the energy output when the system is adjusted from 0° tilt to the 24°optimal tilt, and a gain of 14 % is achieved by adjusting the solar panel seasonally to a tilt angle of 14° in summer and 34° in winter. Therefore, operating the system at a 0° tilt angle, which is a common practice in the study area, reduces the performance and power generating capacity of the SHS. These result are also in agreement with [13] who concluded that, operating the SHS at 0° makes it more vulnerable to negative environmental effects, which reduce the energy output of the system.

The analysis shows that the present methods adopted to provide security for SHS operating in South Africa have a negative effect on the performance of the system. It also points to the need for user education on the optimal use and operational guidelines of SHS, which is necessary for improving the performance and energy output of the system.

Based on the findings from interviews with SHS users the average household uses their systems for 5 hours of lighting, 5 hours of TV and a combined 8 hours of radio and cell phone charging. However, optimization through right sizing of the load shows that the design and install capacity of the SHS (75 W_P PV, and the 100 Ah, 12V battery unit) can only sustain reliable energy supply for 3 hours of light, 3 hours of TV, and a combined 4 hours of radio and cell phone charging. Optimization of the standard and overloaded systems using PVSYST solar software indicates that, to have a reliable energy supply under the standard system the capacity of the SHS should be increased to (114 W_P, 150Ah, 12V battery), and the right capacity for the overloaded system is (214 WP, 283 Ah, 12V battery). Therefore, operating the system in the standard and overloaded condition without right sizing the system creates excessive energy demands on the system. This is indicated by the high levels of loss of power supply indicated by the LOLP over the year as shown in section 4.2. Operating the SHS under the standard and overloaded conditions, results in loss of power to the load for 4081 hours and 6176 hours respectively out of 8760 hours in a year. Optimizing SHS operation ensures uninterrupted power supply to the load. This effect is more pronounced when the seasonal tilt is used on the standard system, in which case the probability of loss of power supply to the load is reduced by 7.4%. When the optimized system is tilted at 0° the loss of load probability rises from zero to 7.5%, and when the overloaded system is operated using seasonal tilt, the ability of the seasonal tilt to sustain energy in the system is reduced to 1.3%. This shows that as more energy is demanded from the SHS the ability of the system to sustain energy delivery to the load decreases. If the user is not informed regarding the power limitations, correct usage of the SHS, and the consequences of drawing excessive energy from the system, then there is no incentive for them to limit their power consumption in line with the optimized system.

In spite of the small generating capacity of the SHS, users' usage pattern exacerbates the situation. Although the users are to blame to some extent, they are forced to take additional measures to safe guard their systems due to the failure of the government to perform its statutory duty. Most designs applied to mitigate solar panel theft have met with little success [49]. Therefore, much of the blames should be laid at the doorstep of the government and energy services providers for alienating users from the program. The users of the equipment need to be carried along with the program through creation of awareness on the operation of the systems, in addition the government needs to provide adequate security to protect the lives and properties of the off-grid rural population.

The results presented here indicate that the usage pattern of the battery affects its life span. The calculated life expectancy for the optimized system shows that the battery can last for about ten years if used correctly. The life expectancy of the optimized system increases in about two fold when compared with the standard and overloaded systems. Frequent discharge of batteries accompanied by inadequate energy generation from the solar panel is responsible for the reduced life expectancy of the batteries in the standard and overloaded systems. The reduction in generating capacity of the solar panel and loads beyond the capacity of the SHS also have a negative effect on the SOC and DOD for the standard and overloaded systems, also affecting the battery life. The results from the survey show that the average lifetime of the batteries is even lower than the results obtained here. This is because our investigation is based on the 75 Wp SHS which has control units, with automatic controls for the charging and discharging processes, which help to increase the battery life to about 5 years in the standard and the overloaded systems. However, some of the old systems mostly 50 W_P SHS currently in use in South Africa do not have automatic control functions. As a consequence most batteries are frequently discharged. The proximity of the SOCs and life expectancies for the standard and overloaded systems is due to the control function which prevents full discharge. Moreover, the overloaded system is at the optimal tilt albeit with a bigger load, while the standard system is at 0° tilt, with less energy but with a smaller load, so the impact of increased load is more pronounced in the loss of power supply to the load (represented by LOLP) as shown in Figs. 4- 5. Data from the energy service providers indicate that in practice the battery life of these systems is between 2-3 years. According to the management staff of Kwazulu Energy Services Company, between 25-30% of all the batteries are replaced annually due to incorrect use and abuses such as bypassing of charge controller to obtain electricity direct from the battery and connection of cheap non-sine wave inverters that drains excessive energy from the battery.

The economic analysis indicates increased overhead cost of the SHS as a result of overutilization and placement of the panels at the non-optimal tilt. Using the system in the overloaded and standard conditions has negative impacts on the LCC, the ALCC and the UCE. The economic cost of the optimized SHS is lower than those of the standard and the overloaded systems. The UCE is reduced by 22%-33% when the operation of the SHS is optimized compared to the standard and the overloaded systems.

This analysis explains the link between the operation of SHS and the economic losses. The current usage pattern reduces the energy output and reliability of the system, which in turn reduces the SOC of the batteries with a corresponding increase in their DOD. This leads to a reduction in the life time of the battery, which also increases the LCC, ALCC and the UCE. The reduction in battery life means that more batteries have to be replaced within the life cycle of the SHS. This ultimately adds to the financial burden of the energy services providers, who are currently grappling with the issues of non-payment of Electricity Basic Services Support Tariff (EBSST) subsidies and service charges by the municipalities and households respectively. This situation affects the sustainability of the SHS program in South Africa and may be one of the reasons why some of the energy services providers have withdrawn from the program. The results support the views of [29] on the need to carry the locals along with the project. The energy service providers are faced with these losses due to their failure to carry the locals along with the SHS program.

5.1 Recommendation

Solar panels are being used at a non-optimal angle in the study area due to the risk of theft. Various methods have been adopted to curb the incidence of solar panel theft with little or no success. Responses from households and the relevant staff of the energy services providers (Solar Vision, NuRa Energy and Kwazulu Energy Services) indicate that the use of community vigilante groups for community policing and the involvement of the police have not been effective because policy post are located at the municipal and district headquarters and maintenance of the vigilante group is difficult. Technical solutions like the use of radio frequency identifier (RFID) and integration of alarm systems to the panels have been proposed in past. According to NuRa Energy, these systems cost between 400 and 600 ZAR per installation and need maintenance and replacement of parts over time; this cost is too high for most of the SHS users. In addition, RFIDs do not prevent solar panel theft but only assist in the recovery. This situation also reflects the observation of [49] that various efforts to curb theft of solar panels have been largely ineffective. Information from victims indicates that 80-90% of thefts occur at night, and most others occur when owners are not at home. Therefore, the habit of taking the panels indoors at night will reduce the incidences of theft considerably.

5.1.1 Proposed benchrack mounting system for solar home systems

This study recommends a cheap method for the optimization of SHS operation in order to mitigate the losses associated with these practices, by using a Bench-Rack Solar Panel Mounting System. The Bench-Rack is a mobile system that can be taken indoors at night for safe keeping, thereby reducing the possibility of theft. Spurred by the above enumerated advantages evident with the optimization of SHS operation and the realization of the low income level of the households using solar home systems in developing countries, we propose the Bench-Rack Solar Panel Mounting System to help households reduce losses associated with the operation of their SHS by making it easy to operate in the most cost effective manner while maintaining security. The Bench-Rack system is designed to allow the solar panel to operate at the optimal tilt angle (β) as well as seasonal tilt angles for summer and winter. Fig. 7 shows the system set in position 2, at the optimal tilt angle (β). The clamp arm can be adjusted to a tilt of (θ-10) for summer (October-March) by moving to position 3. During winter (April-September) it can be adjusted to a tilt angle of (θ+10) by moving it to position 1. The advantage of the Bench-Rack system is its simplicity; all parts are made of wood and are detachable for easy movement. In line with the new security measures in place, it can be taken indoors at night for safe keeping. It is therefore adaptable to the current operating condition of SHS in the vulnerable areas of South Africa. The use of the Bench-Rack mounting system is intended to optimize the operation of SHS by reducing losses associated with the current practice of placing the system on the ground at 0° tilt angle. It also addresses the issue of overloading the system by operating security lights for extended hours, since the system is moved indoors at night for protection against theft, negating the need to use lights for extended hours.

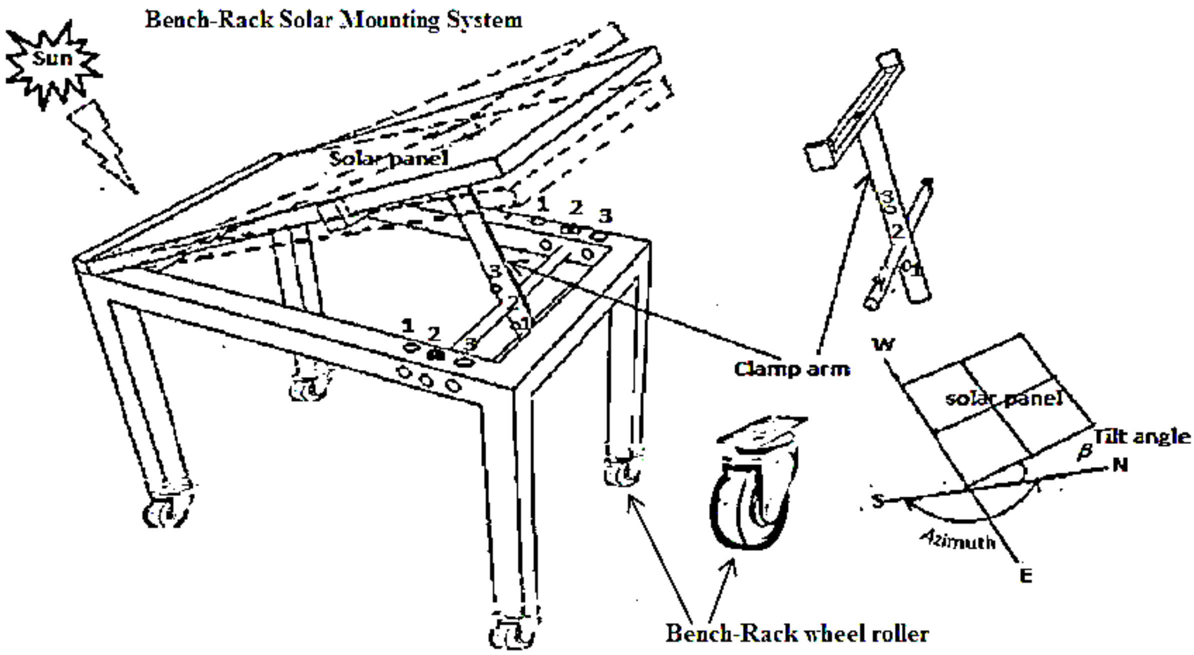

Fig. 7 Bench-Rack systems showing various positions for seasonal and optimal tilts for solar panels.

Integrating the Bench-Rack mounting system will have little economic impact on the SHS program. The estimated cost of the Bench-Rack System is $31.8 USD (using foreign exchange of 1USD to 9 ZAR). The economic benefit of Bench-Rack system to the SHS program is as follows. The LCC, ALCC and UCE are calculated to be $1289.52, $101.70 and $0.92/kWh respectively. The inclusion of the Bench-Rack mounting system only accounts for 2% increase in UCE, and about 3% increase in both the LCC and ALCC for the optimized system. Therefore, the system provides a cost effective way to achieve both the optimal and seasonal tilt angles with their inherent advantages, thereby maintaining the integrity of the energy supply with limited financial burden on the household.

6. Conclusion

This study has shown that the use of non-optimal tilt angle for solar panels, and the use of outside lights as security light for extended hours to protect SHS against theft have negative consequences on the power output and performance of the system. The energy losses associated with these practices affects the sustainability of SHS program by increasing the overhead cost of the systems. Also the analysis of the reliability of the energy from SHS currently in use in rural South Africa revealed that its undersized, to meet the energy needs of the households the current capacity of the system should be increased.

The use of lights for extended hours overloads the SHS, and placing the solar panels flat on the ground at a non-optimal angle reduces the energy generation capacity. Both actions affect the state of charge of the battery negatively and ultimately degrade the reliability and quality of the power supply. Optimizing the operation of the system can extend the battery life in more than two fold. The economics of owning and operating SHS can be improved when the system is used according to the designed specifications. Optimizing the use of SHS results in a reduction of about 19-26% in the life cycle cost of SHS. In addition, the unit cost of electricity is reduced by 22-33% in households that place their solar panels flat on the ground and those that use the lights for extended hours respectively. The annualized life cycle cost is also decreased by about 23% on the average.

The need to protect solar panels from theft and more importantly the overarching need to meet basic energy needs are motivations for an uninformed user to keep overloading and abusing the SHS. To reduce these deviations from optimal usage, we recommend the optimization of the SHS as demonstrated by the use of the Bench-Rack solar mounting system and the adoption of energy efficient measures for protecting SHS operations in vulnerable regions of South Africa. In addition, the government needs to put more effort in securing the lives and properties of the rural population in South Africa. Education of users in SHS usage pattern and training of local technicians in minor maintenance routines are essential. Training of local technicians will contribute to local job creation over time and reduce power outages from the systems. Our economic analysis shows that the price of not carrying locals along with the program outweighs the alternative; the stakeholders will pay more through frequent replacement of equipment.

Acknowledgements

We would like to thank the locals of Thlatlaganya, Masakele, Malaeneng, Muchipisi, Dumela, and Ndumo Communities for the valued information given to us during the survey. Our profound appreciation goes to Jake Jacobs, the MD of solar vision whose support made the survey a success. Also, we thank Sifiso Dlamini the general manager of NuRa energy for coordinating our survey in Kwazulu Natal province, and we must not fail to mention the positive contribution provided by Vicky Basson, the MD of Kwazulu energy during her interview. We thank Jan Skvaril for his input during the design of the Bench-Rack solar panel mounting system. Special thanks to Hailong Li and Pietro Campana for their criticism of the work which led to a better outcome. We also thank the Swedish International Development Cooperation Agency (SIDA) for their financial support.

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