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The burden of shading and location on the sustainability of South African solar home system program

Chukwuma Leonard Azimoh, Patrik Klintenberg, Fredrik Wallin, Björn Karlsson

Mälardalen University, School of Business, Society and Engineering, Box 883, SE-721 23Västerås, Sweden

CL Azimoh. Tel: +4621101519; Fax: +4621101586; email: leonard.azimoh@mdh.se

Abstract

Most contributions on the issues of sustainability of rural electrification projects have focused on the technology and business models used to drive the projects. The issues of user education and environmental impact on the technology have received little attention, despite the fact that these challenges affect lives of projects after commissioning. The usage pattern of solar home systems (SHS) by most users that placed their solar panels close to obstructing objects, results in shading of the panels, and geographic location of households in the concession areas of the South African SHS program affects the performances of the system. The non-optimal use of SHS is mainly due to lack of user education. Therefore this paper reports on the impact of geographic location and shading of panels on the economics and technical performance of SHS. The study was done by investigating the performance of 75 W_P solar panels operated at two sites in South Africa (Upington in Northern Cape Province and Thlatlaganya in Limpopo Province), the performance of an optimized shaded SHS and a non-shaded one was also investigated. The results show that both geographic location and shading compromise the performance of the systems, the energy output of a solar panel located at Upington is increased by 19% and the state of charge of the battery (SOC) increased by 6%, compared to the panel situated at Thlatlaganya village. Also the life span of the battery is increased by about one year. The SOC of the partially shaded SHS is reduced by 22% and loss of power to the load increased by 20%. The geographical location of the SHS concession areas in South Africa and lack of adherence to the manufacturer's installation specification affects the economics of SHS and the energy output vis-à-vis the sustainability of the program due to reduction in life cycle of the batteries.

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Keywords: Sustainability; Rural electrification; Solar Home System; Geographical location; Shading; State of charge.

1. Introduction

The sustainability of solar home systems provided through the South African SHS program has been challenged due to various factors. Previous reports have cited reasons like grid encroachment, institutional delays in payment of subsidy funds, payment aversion by some households, and the inability of the system

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to support establishment of small scale businesses among the local in order to improve payment capability of the households [1][2][3]. Sustainability of the SHS program is also affected by the business models used to drive the program, high costs, affordability and policy constraints [3], [4]. A review on the effectiveness of SHS in Africa indicates that the inability to meet the energy needs and high costs limit the success of SHS programs in Africa [5]. Another review of the experience of SHS in developing countries revealed that inadequate infrastructure affects sustainability of SHS programs [6].

Most discussions on sustainability of SHS programs have focused on financing mechanisms, technologies and policies used to drive the program. The technical challenges resulting from shading and location of project sites have been addressed purely from an engineering perspective. A report stated that shading a small part of the PV cells could result in significant reduction of the power output [7]. Parallel-connected PV cells have been found to be less susceptible to shading than series-connected ones [8]. Assessments of impact of shading on the performance of PV cells using computer-aided simulation have been reported in publications like [9]. The effect of geographic location on the performance of PV systems was presented in a study in Canada that showed that geographical dispersion of PV affects the energy output [10]. Most of these reports have paid attention on power losses as a result of reduced power production from PV systems originating from shading and geographical locations, less attention has been paid to the attendant economic losses as a result of the reduced life cycle of the battery. This paper therefore focuses on the effect of energy losses on the life cycle of the battery, which affects the sustainability of SHS programs as a result of increased overhead costs.

1.1 Solar Irradiation

The average daily solar radiation in South Africa is between 5 to 8 kWh/m^2/day [11]. The solar irradiation profile shows that there is high availability of sunlight in South Africa in contrast to Europe and USA where daily solar radiation is about 2.5 and 3.6 kWh/m^2/day respectively [11].

1.2 Shading

The reason why shading affects PV modules is because it behaves like a diode that allows current to flow only in one direction. The PV cell is made of negatively charged semiconductors mostly crystalline silicon (n) and a positively charged semiconductor substance, mostly crystalline silicon (p). When the electrons in the atom absorb light energy (photons) due to photoelectric effect, they get excited and achieve enough energy to reach the valence band or sometimes get freed. The freed electrons move from the n-type semiconductor to the p-type semiconductor and this movement is the cause of current flow in the cells, which generates the electricity. Since atoms do not move an equilibrium position is reached with a potential of 0.6 volts between the p-n junctions. For conduction to take place this equilibrium most be offset and this requires extra energy from the solar radiation to achieve. Since the current flows in one direction any obstruction due to shading of the PV cells will affect the output of the cells because the current are forced to flow in the reverse direction in the shaded cells. Shading reduces the energy output from PV in two fold by obstructing the solar irradiation reaching the cells (energy input) and by increasing the energy losses through reverse bias current through the shaded cells [8]. A typical equivalent circuit for a PV cell using single diode model is shown below in Fig. 1. Empirical evidence from the South African SHS program revealed that most users are using the system non-optimally. The reason for non-optimal use is often due to the high risk of theft and sabotage of systems when placed in their appropriate position on rooftops. Fig. 2 depicts an example of a shaded panel at one of the households using SHS in South Africa. The panel is placed on the ground, in front of the door to prevent theft.

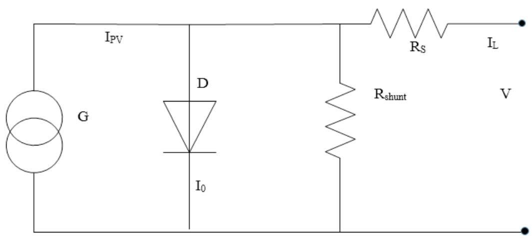

Fig. 1. Equivalent circuit of s PV cell

Fig. 2. Shaded SHS in South Africa

2. Methodology

The geographic locations used for this simulation are Thlatlaganya village in Polokwane municipality in Limpopo province (latitude -23.5°N and longitude 29.4°E) and Upington Town, Ilkhara Hais local municipality within ZF Mgcawu district municipality in Northern Cape Province (-28.4°N and 21.3°E). In the study, Meteonorm™ weather software [12] was used to obtain the weather information of Polokwane municipality. The optimal tilt angle for Thlatlaganya village (24°) and Upington Town (28°) was determined using TRNSYS-Winsun solar energy software [13] under the fixed tilt geometry system. PV.SYST™ solar energy software [14] was used to investigate the performances of the battery at Upington and Thlatlaganya and the performances of the optimized shaded and unshaded SHS operated from Thlatlaganya. A seasonal tilt of (θ-10) for summer and (θ+10) for winter was used in accordance with [15]. The simulation is carried out with 5% loss of load (LOL) factor and three days of autonomy using 75 W_P, 100 Ah, and 12 V battery unit and a charge controller for the SHS specification.
The life cycle of the battery was calculated using equation (1) [16].

$$Bat_{lifecycle} = (89.59 - 194.29T) * e^{(-1.75*DOD)} \quad \ldots (1)$$

PV surface area is derived from the equation (2) [17].

$$P = AG_{T1}\eta_{mp}\eta_e \quad \ldots (2)$$

Where, P is the output power, A is the PV surface area, G_{T1} is incident radiation, η_{mp} *and* η_e are the efficiencies of the PV and any power conditioning equipment respectively. A PV surface area of 0.7 m^2 (equipment specification) is used and while power conditioning equipment is excluded from the analysis.

3. Results

3.1 The effect of geographic location on the solar irradiation on SHS performance

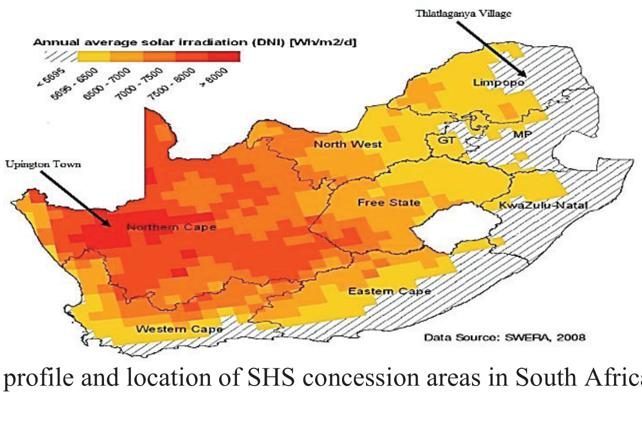

Fig. 3. Solar irradiation profile and location of SHS concession areas in South Africa.

The assessment of the solar irradiation profile of South Africa shows that location of households within the SHS concession areas in Limpopo, KwaZulu-Natal and Eastern Cape Provinces has relatively low solar irradiation compared to the other provinces in South Africa as illustrated in Fig. 3 above. Thlatlaganya (Limpopo) receives average of about 5.84 KWh/m^2/day of solar irradiation, while Upington (Northern Cape) receives about 6.17 kWh/m^2/da.

3.2 The impact of location on the performance of SHS

Simulation with PVSYST shows that a SHS operating in Upington increases the SOC of the battery by about 6%, in contrast with a SHS located in Thlatlaganya village. This led to the extension in cycle life of the battery by more than one year (Table 1). Also, the energy output is increased by 19% for a SHS operating in Upington. A SHS operating in Thlatlaganya (with 2127 KWh/m^2 solar irradiation and module efficiency of 9%) will require an increase of panel surface area by about 14% to achieve the same power output with that located at Upington village (2279 KWh/m^2/year). The economic impact of this is that less battery will be replaced during the life of the SHS and the PV size required to achieve the same power output is reduced, hence less financial burden on the energy providers.

Table 1. The effect of location on the performance of SHS

	Thlatlaganya	Upington
SOC of SHS (%)	86	89
Energy output of SHS (kWh/m^2/yr.)	129	154
Battery Life Cycle (year)	10.22	11.36
Required solar panel area (m^2)	0.8	0.7

3.3 The impact of shading on performance of SHS

The investigation shows that shading also affects the performances of solar panels negatively. Shading increases the probability of loss of power supply to the load by about 20% (Table 2). The power output is also reduced by about 22%. An optimized system operating in Thlatlaganya for instance could have the SOC reduced by about 36% as result of partial shading of the surface area. The reduction in in SOC is as illustrated in Fig. 4. This also led to a reduction in the energy output by about 22%, this reduction is illustrated in Fig. 5.

Table 2. Impact of shading on the performance of a SHS

PV-System	SOC %	LOL Pr %	Power @MPP (W)	Power loss (W)
Unshaded system	84	0	439	0
Shaded system	52	20	343	96

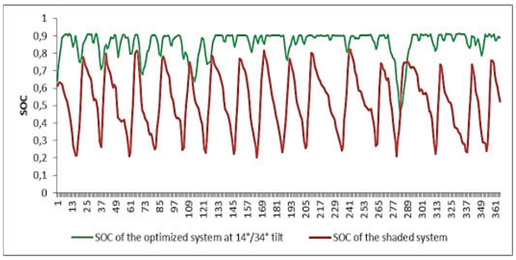

Fig.4 The SOC of unshaded and shaded SHS

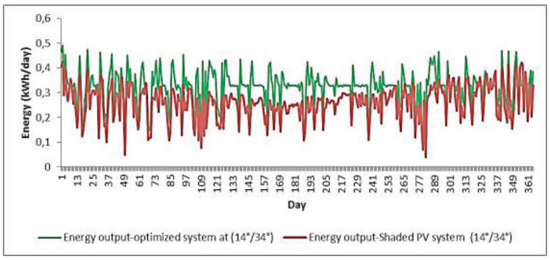

Fig.5.The Energy output of unshaded and shaded SHS

4. Discussion

The results show that the SHS could perform better in terms of energy output and reduce the economic cost of operation, if the concession areas were located in the higher solar belt of South Africa. To improve the performance in these areas the technology has to be adapted to the environment by increasing the size of the solar panels. This suggests that the SHS currently used in the concession areas are not performing optimally. The reduction in the energy output is consistent with the findings of [10]. The decreased energy output means that less energy is available to charge the battery, this invariably leads to disproportionate discharge of the battery. Short battery life, frequent and high cost of replacement motivates the use of cheap batteries [18]. The use of cheap batteries increases the replacement rate with increased cost. The reduction in life expectancy of batteries ultimately affects the economics and the sustainability of the SHS program negatively.

Shading of solar panels in the investigated areas is due to two factors, one is lack of adherence to the designed and installation specification by the users, the other is due to natural obstructing objects like highlands and mountains. The energy output is reduced by increasing energy losses in the shaded cells and by reducing the input to the cells, this is conformity with [1]. The resultant effect is reduction in the battery life due to low state of charge and frequent discharge. Therefore, situations and mechanisms that reduces energy input to the battery affects the battery negatively, as evident with the case of shading and reduced solar irradiation due to geographic location.

5. Conclusion

The geographic location of the Solar Home System (SHS) in environments with low solar irradiation has the potential of affecting the sustainability of the South African SHS program, through increased financial burden on the energy provider as a result of frequent replacement of batteries due to reduced state of charge (SOC) and the resultant reduction in the life cycle of the batteries. This study shows that the energy output and life cycle of batteries were improved when the system is operated at Upington with higher solar irradiation than Thlatlaganya with lower irradiation. The SHS in use at the concession areas of South Africa are producing less energy per unit area of the solar panel due their geographical locations, hence more PV size is required to produce the same amount of energy at Thlatlaganya compared to when the SHS is located at Upington with higher solar irradiation.

Shading also affects the performance of SHS by reducing the energy output, the state of charge of the battery and by extension of the life cycle of the battery. Operating SHS under shaded condition could result in about 36% loss in energy production in Thlatlaganya village. Most households are ignorant of this due to lack of user education on the operation and usage guidelines of SHS, also households located at the knee or with close proximity to highlands and mountains are susceptible to shading in winter, when the shadow length is elongated. Location and shading of SHS has the potential of affecting the economics of SHS through reduced life cycle of the battery. Reduction in the life cycles of battery could affect the sustainability of SHS through increased overhead cost, as a result of frequent replacement of batteries. The households using SHS in South Africa need to be enlightened on the optimal usage of the system, in line with the manufacturer's specification.

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