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Comprehensive techno-economic and environmental impact study of a localised photovoltaic power system (PPS) for off-grid communities

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ABSTRACT

This study presents detailed techno-economic and environmental impact assessment of a photovoltaic power system (PPS) for a small off-grid community. The PPS is designed to meet a community's load demand of ~63,900 kWh, with an annual load growth of 1% over a 25-year project lifespan. Its performance is assessed in terms of the power output, energy production, yield and losses, and the efficiency. Furthermore, detailed battery state of charge (SoC) and reliability analysis is presented. The paper uses the life cycle evaluation technique to analyse the system's economic and environmental performances, using Bununu community in Bauchi State, Nigeria as a case study. Results show that the loss of energy probability and the availability of 0.44–1.09% and 98.91–99.56%, respectively, can be achieved with PPS sizes of 50–62.7 kW. In addition, the proposed PPS's life cycle costs range from ~48 to 49.5% of the values obtained for the diesel plant. The PPS's life cycle emission rate is 50 gCO_2-eq/kWh, which is ~7.9–8.7% of the diesel plant's emission rates. The proposed PPS's GWP ranges from 4307 to 5400 $kgCO_2$-eq. These outputs are evaluated by comparing them with some existing results in the literature, and can be useful for planning stand-alone PPS for remote locations around the world.

1. Introduction

As renewable energy technologies continue to attract a growing interest around the globe, it is crucial to understand the techniques that are necessary for designing and developing them. It is important that these techniques include the technical, economic, environmental and the reliability aspects. The PPS is currently considered as an option for providing electricity to isolated parts of the globe. Therefore, there is optimism that it can help to improve the energy situation of ~1.3 billion people that do not have access to modern electricity supply [1–11].

It is estimated that ~55% of the 1.3 billion people live in the sub-Saharan African region [11]. The region's electricity deficit rate could be reduced by harnessing and maximising its huge solar energy resources. In this paper, Nigeria is used as a case study for the proposed localised PPS. The country has a population of about 182 million, with only ~40% having access to the national grid [4]; the largest percentage of the population, is, therefore, left without access to modern energy supply. The centralised electricity system is weak and inefficient. It is not able to adequately support the users' electric load demands. As a result, most on-grid communities have little or no difference from the off-grid communities. With Nigeria's abundant solar energy resources, it is possible to electrify the off-grid and energy-poor communities through solar electricity systems.

Moreover, based on our experience, there is an increased solar photovoltaic system failure in Nigeria. This is due to the lack of knowledge and techniques for the proper design of such systems in the country. Many stand-alone photovoltaic systems have been designed without adequate considerations for losses and the possibility of users' energy demand growth. This problem is one of the factors inhibiting the widespread use of the solar electricity systems in the country. This research is motivated by the mentioned challenges, and it focuses on how to address them by proposing a PPS based on the global engineering standards, practical experience and existing knowledge.

Several studies have discussed the solar power generation systems. These are particularly aimed at advancing the knowledge and promoting the use of PV-based systems, especially in countries having huge solar energy resources. Therefore, reference is made to these studies, and they form a part of the background for this paper. A feasibility study and energy conversion analysis of stand-alone hybrid renewable energy system has been discussed [1]. The paper focuses on the techno-economic assessment. The techno-economic sizing of off-grid hybrid renewable energy

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Nomenclature

A.T.L	array power output after temperature losses (kW)
A.O.L	array power output after other losses (kW)
B_c	battery capacity at a particular time (kWh)
B_c(min)	minimum battery capacity (kWh)
B_c(max)	maximum battery capacity (kWh)
B_{cp}	battery capacity based on the desired *DOD* (kWh)
DOD	depth of discharge (%)
D_a	days of autonomy
d_{rf}	derating factor
d_{sf}	design safety factor
E_d	load demand (kWh)
E_{PR}	energy produced by the PV system (kWh)
E_{dif}	energy difference (kWh)
G_a	solar irradiance of the site (W/m^2)
G_{STC}	solar irradiance at STC (1 kW/m^2)
LOE	loss of energy
L.D.T	losses due to temperature (kW or kWh)
MDOD	maximum depth of discharge (%)
N	number of batteries in the battery bank
NOCT	nominal operating cell temperature (°C)
O.L	other losses (kW or kWh)
P_{ref}	reference output of the PV array (kW)
P_f	final output of the PV array (kW)
P_{mp}	rated module power (W)
SOC	state of charge (%)
SOC_{min}	minimum state of charge (%)
SOC_{max}	maximum state of charge (%)
T_c	cell temperature (°C)
$T_{c,STC}$	cell temperature at STC (°C)
T_a	ambient temperature (°C)
η_{new}	actual efficiency (%)
η_{Ref}	array efficiency o at STC (%)
V_s	battery system voltage (V)
η_{rtp}	round trip efficiency (%)
α_p	temperature coefficient of power (%/°C)

system for rural electrification has also been presented, using a location in Sri Lanka as a case study [2].

The development of a PV plant for remote residential use has been discussed, focusing on the socio-technical-economical perspective [4]. The authors employ a detailed social analysis to propose an electricity system for an isolated community. Also, the assessment of decentralised hybrid PV-diesel power system has been reported for the northern part of Nigeria [5]. The authors employ the HOMER simulation tool to model an energy system for the isolated community of around 1500 households.

A paper has also been presented focusing on the study of a household electrification system [12]. The author majorly assesses the off-grid homes' load demand profiles, which can be useful for designing suitable PV systems. Furthermore, a research has been reported for electrical power supply for rural parts of Nigeria [13]. This study compares the life cycle costs of the solar PV, diesel/gasoline and the utility systems. Also, a study is conducted on how renewable electricity-based supply may be possible in Nigeria. This work focuses mainly on the assessment of Nigeria's renewable energy potential, which can be useful for future planning [14].

The assessment of hybrid renewable power sources for rural electrification has also been discussed, using Malaysia as a case study [15]. Furthermore, the design and costing of a stand-alone solar PV system has been presented, using a rural household in Tanzanian as a case study [16].

The techno-economic feasibility of renewable energy resources for water pumping in sub-Saharan Africa has also been discussed, with a focus on central Nigeria [17]. An off-grid wind/PV community electrification project has been evaluated [18], while a study is also discussed on the viability of grid-connected solar PV energy system in Jos, Nigeria [19]. The optimal green energy management of on-grid and off-grid electrification systems have also been presented, using Nicaragua as a case study [20].

The studies mentioned above provide useful knowledge and background for this current paper. The majority of the studies employs the techno-economic evaluation technique for proposing different electricity generation models. A few of the studies also considers the energy losses [1,4,16,20]. However, most of these studies do not discuss the energy losses, battery SoC, reliability, load growth and the life cycle environmental impact of the energy systems [2,5,12–15,17–19]. A number of them that considers the energy losses does not also consider the battery SoC, reliability, load growth and the life cycle environmental impact analysis [4,16,20]. In addition, one of the papers also evaluates the battery SoC, but does not discuss the reliability, load growth and the life cycle impact [1]. These knowledge gaps and the mentioned energy challenges in Nigeria will be addressed in this study.

This paper, therefore, proposes a PPS for a small remote community, based on the global engineering standards, i.e. IEEE and IEC guidelines [21–25]. It carefully examines the worst-case scenarios, i.e. the location's lowest solar irradiation and the users' highest load demands. The PPS is modelled to adequately meet a community's load demand of ~175 kWh/day (i.e. ~63,900 kWh/yr), plus an annual load growth of 1%, over a 25-year project lifespan.

A design safety factor (d_{sf}) is also introduced into the array sizing model so that the PPS is able to compensate for the energy losses. A d_{sf} of 1.2 is first used based on the IEEE 1562 standard [21], and the PPS is analysed to determine whether or not it is able to meet the specified load demand requirement. The study considers the scenarios of PPS capacity increase and load demand reduction, as means to ensure reliable energy system.

The PPS performance is assessed in terms of the power output, energy production, normalised yield and losses and the efficiency. Detailed battery state of charge (SoC) and reliability analysis is also presented. The reliability analysis is achieved in terms of the unmet energy demand, loss of energy probability and the availability metrics. The paper also uses the life cycle assessment technique for evaluating the system's economic and environmental performances, using Bununu community in Bauchi State, Nigeria as a case study.

The proposed PPS is assessed by comparing its performance with the values published by the International Energy Agency Photovoltaic Power System (IEA PVPS) [26] and some other results reported in the literature [27–35,64–68]. The PPS analysis results are also compared with that of a diesel power generation plant.

The remainder of the paper is structured as follows: Section 2 focuses on the background of the isolated community; Section 3 concentrates on the system design approach; Section 4 presents the results and discussion, while Section 5 concludes the paper.

2. Background of the isolated community

This paper proposes an energy system for a small isolated community in Bununu, Bauchi State, Nigeria. This location is within