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Techno-economic and life cycle environmental performance analyses of a solar photovoltaic microgrid system for developing countries

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ABSTRACT

This paper presents detailed techno-economic and environmental analyses of a SPM (solar photovoltaic microgrid) for remote communities. The SPM is modeled to support a yearly load growth of 2% over a project life of 25 years, with a base case demand of 63,875 kWh/yr. The PV and the battery performances are carefully evaluated. We use the unmet demand, loss of energy probability and the availability indices to determine the system reliability. LCC (Life cycle cost) and LCI (life cycle impact) analyses are used to assess the economic and the environmental performances of the SPM. A small community in Gusau, Zamfara State, Nigeria is used as a case study, and we obtained SPM capacities of 55–82.5 kW with availability values of 96.86–98.74%. The life cycle costs of the SPMs range from 425,500 to $ 470,472, which is about 47–50% of the values obtained for the diesel power system. The emission rate of 56.7 gCO_2-eq/kWh is obtained, which is 8.15–9.84% of the emission rates of the diesel system. The global warming potential of the SPM systems ranges from 5178 to 7765 kgCO_2-eq, while the energy payback time and the energy return on investment are ~1.46 years and 17, respectively. These results can be useful for conceptualizing and planning PV microgrids in developing countries.

1. Introduction

Renewable energy technologies continue to become popular in the agenda of most governments, policy makers, energy system developers and the concerned individuals around the world [1]. Yet, as these systems attract growing interests, it is crucial to understand how they are planned, for achieving successful energy supply and long-term viability.

Planning renewable energy systems does not only require the technical considerations, but also involve the economic and environmental analyses. These are required for providing insights into the practicality of the proposed systems. Renewable energies have a huge potential to meet the energy needs of ~1.3 billion people in the world, who do not have access to modern energy supply [1–13]. SPM (Solar photovoltaic microgrid) systems, among others, are identified as a promising option for electrifying the off-grid parts of the world, especially those areas with huge solar energy resources. Therefore, this study proposes an SPM system for a small isolated community in Guzau, Zamfara State of Nigeria.

Several studies have been published on solar electricity supply systems, which we refer to in this current paper as a background. The author in Ref. [6] presents the feasibility of hybrid solar PV-diesel systems for northern part of Nigeria by using HOMER tool, while the study in Ref. [7] focuses on global progress of PV technologies and development of solar panel plant and module performance analysis. The authors in Refs. [8,9] presented the social, economic and environmental benefits of decentralized solar PV systems for energy-poor households by using HOMER.

A research on clean development mechanism projects for developing countries is presented in Refs. [10], which focuses on the techno-economic analysis of PV systems compared to a diesel energy system. Olatomiwa et al. in Ref. [14] presents the techno-economic feasibility of different hybrid renewable power supply systems for RHC (rural health clinics) in six geo-political zones of Nigeria. The authors in Refs. [15,16] discussed solar energy systems for rural development in Nigeria.

The study in Ref. [17] highlights the possibility of meeting the users' energy demands in Nigeria by 100% renewable electricity systems. The authors in Refs. [18,19] also used HOMER to evaluate

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Nomenclature

A_j	number of energy users within the category *j*
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 (mn)	minimum battery capacity (kWh)
B_c(mx)	maximum battery capacity (kWh)
B_c	battery capacity based on the desired *DOD* (kWh)
c-Si	crystalline silicon
DOD	depth of discharge (%)
D_a	days of autonomy
d_r	derating factor
d_{sf}	design safety factor
d_{ij}	duration of operation of load *i* within category *j*
E_c	load demand (kWh)
E_{Pr}	energy produced by the PV system (kWh)
E_{dff}	energy difference (kWh)
F_c	fuel consumption rate
G_i	solar irradiance of the site (W/m^2)
G_{stc}	solar irradiance at STC (1 kW/m^2)
inv	inverter (kVA)
LOEP	loss of energy probability
L.D.T	losses due to temperature (kW or kWh)
L_i	inductive load (kW)
L_o	other loads (kW)
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_{out}	operating output power of diesel gen (kW)
P_{rat}	rated diesel gen power (kW)
n_{ij}	number of loads *i* within category *j*
P_{rf}	reference output of the PV array(kW)
P_f	final output of the PV array(kW)
P_{mp}	rated module power (W)
r_{ij}	rated power of the load *i* within category *j*
SoC	state of charge (%)
SoC_{mn}	minimum state of charge (%)
SoC_{mx}	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_{rf}	array efficiency o at STC (%)
V_s	battery system voltage (V)
η_{rtp}	round trip efficiency (%)
α_p	temperature coefficient of power (%/°C)
i	kind of loads or appliances (e.g. light bulbs, TVs etc.)
j	category of users (e.g. residential etc.)
X_1	diesel gen fuel curve slope
X_2	fuel curve intercept coefficient
UD	users' demand in %

techno-economic performance of different energy configurations. They also analyzed the annual carbon emissions of the proposed systems. The research reported in Ref. [20] focuses on the techno-economic feasibility of renewable energies for water pumping in sub-Saharan Africa. Furthermore, techno-economic studies for PV have been presented in Refs. [21–24] for remote households in different countries — New Zealand, Indonesia, United Arab Emirates and Saudi Arabia.

These studies provide a good background for techno-economic assessment of distributed energy generation technologies. Some of them also evaluate the environmental impact of the systems from the point of view of annual carbon footprints displaced. However, we found that the studies presented in Refs. [6,8–11,14–23] do not consider the assessment of PV energy losses, battery SoC (state of charge), system reliability and the load demand growth, which are also crucial for planning and decision-making purposes. Though the papers in Refs. [7,12,13,24] discuss energy losses, they do not consider battery SoC, reliability and users' energy demand growth. Some of the papers discuss the environmental analysis in terms of the amount of CO_2 saved by the PV system, but none of the studies in Refs. [6–24] considers the environmental assessment from the perspective of life cycle impact. We intend to address these knowledge gaps in this current study.

This research proposes a SPM (solar photovoltaic microgrid) system for a small remote community in Gusau, Nigeria. The design approach for this system is based on the worst-case scenario, guided by global engineering standards [25–29]. We introduce a design safety factor (d_{sf}) of 120% to the microgrid sizing model to determine the baseline rated capacity according to IEEE standard 1562 [25]. The SPM is then simulated and analyzed with HOMER software to find out if it can satisfy the annual energy requirements of 63,875 kWh without load growth. Basically, two scenarios are considered in a situation where the SPM with a d_{sf} of 120% cannot satisfy the users' energy requirements over the year. These are the increase of SPM capacity and the load demand reduction. We consider these two scenarios to provide different options for planning and decision-making.

The proposed microgrid model seeks to achieve a high reliability all year round. In addition, because it is possible for the users' energy demands to increase over time, we therefore consider an annual load growth of 2% over the SPM lifespan of 25 years. The performance of the SPM is evaluated in terms of the power output, yield, losses, efficiency, and the battery SoC, while its reliability is assessed by using the unmet load, LOEP (loss of energy probability) and the availability metrics. LCC (Life cycle cost) and LCI (life cycle impact) analyses are used to assess the economic and the environmental performances of the SPM. The environmental impact analysis is achieved in terms of the fuel saved, life cycle emission rate, GWP (global warming potential), CED (cumulative energy demand), EPBT (energy payback time) and EROI (energy return on investment). The simulation results are compared with some related research in the literature [30–39]. It is expected that the results will be useful for better understanding of stand-alone PV systems, thus, helping to address the problem of system failure in Nigeria, including other developing countries.

The remaining part of the paper is structured as follows: Section 2 focuses on the background of the community; Section 3 discusses the methodology; Section 4 presents the results and discussion; Section 5 evaluates the results, while Section 6 concludes the paper.

2. Background of the community

This paper proposes microgrid solutions for a small off-grid community in Gusau, Zamfara State, Nigeria. The community is