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Community-based hybrid electricity supply system: A practical and comparative approach

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HIGHLIGHTS

- A practical community-based PV/diesel model is proposed.
- The model can support the users' worst-case demand of 175 kWh/d.
- The model has a higher availability compared to PV-only and diesel-only options.
- The life cycle cost of the model is ~25% less than that of a diesel-only option.
- The CO_2 emission of the model is ~14% of that of a diesel-only option.

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ABSTRACT

This paper discusses the development of hybrid electricity supply system (HESS) for a remote community, which takes our previous study some steps further. Previously, we have proposed a PV-based system to electrify 24 houses during the dry and wet seasons. While this system can support the users' demand during the dry season due to high solar irradiance, load reduction is inevitable during the rainy season to manage the available electricity. The users will be constrained to limit the operation of certain appliances, especially the fridges during such a period. Therefore, this new study introduces a diesel generator to the existing PV model to create the HESS, which is expected to address the load reduction issue, thus, meeting the users' worst-case demand at all the seasons. The HESS is modeled in DIgSILENT environment; the design methodologies and analyses are based on the global engineering standards and practical experience. Its techno-economic and environmental performances are then compared with those of PV-only and diesel-only systems for decision-making. Results reveal that the HESS is a better option in terms of ensuring the maximum comfort of the users during the two seasons, with relatively higher reliability. Though it has the highest initial capital cost, its life cycle cost, fuel consumption and carbon footprint are lower than the values obtained for the diesel-only option.

1. Introduction

As modernized as the world seems to be, there are still about 1.3 billion people in the global community who live without access to modern electrical energy supply [1–9]. This development connotes a low standard of living, backward social and economic lives for such people in their various local communities. Electricity supply through renewable energy technologies is currently recognized, not only as an option for mitigating the global carbon emissions, but also a practical means of electrifying the energy-poor areas around the world, thus, improving the lifestyles of the people. However, the implementation of such technical solutions requires sound planning strategies and processes, which needs to be part of the considerations and efforts made by the researchers, engineers, installers, etc.

In the energy research parlance, techno-economic assessment [4,10] is a popular approach employed for planning electricity generation systems, which deals with the evaluation of such systems both from the technical and the economic viewpoints. It is essentially a relevant technique that is being employed by researchers and planners for energy design and modeling purposes, so as to analyze the technical feasibility and the economic advantage of the system, during the planning/development phase. Some of the several existing works that are based on this approach are reported in [11–26]. The performance analysis of hybrid photovoltaic/diesel electricity system has been discussed by Lau et al. [11], under the

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Malaysian environmental conditions. The study employs techno-economical evaluation to investigate the feasibility of the energy system. The assessment of economic viability for PV/wind/diesel hybrid energy system in southern Peninsular Malaysia has also been presented in [12]. The authors have used hybrid optimization model for electric renewable (HOMER) to determine the technical feasibility and the cost implication of the energy design.

Techno-economic technique has also been employed by the authors in [13] for modeling a PV–diesel–battery hybrid power system, for a remote location near Rafha, Saudi Arabia. The techno-economic feasibility of the irrigation system for the grassland and farmland conservation in China is presented in [14]. This is conducted to compare the photovoltaic with wind power water pumping systems. Chandel et al. discusses solar PV water pumping system for irrigation and community drinking water supplies, with focus on the techno-economic and environmental analyses [15]. The authors in [16] discusses the techno-economic analysis for the hourly prices of decentralized PV systems, which tests the impact of pricing simplification models on revenues and NPV. The techno-economic analysis of Domestic High Consumption Tariff niche market for photovoltaic systems in the Mexican household sector is presented in [17].

A paper on feasibility and sensitivity analysis of a stand-alone photovoltaic–diesel–battery hybrid energy system in the north of Algeria has also been discussed [18], which centers on the technical and economical considerations. The paper in [19] also reports the techno-economical analysis of stand-alone hybrid renewable power system for Ras Musherib in United Arab Emirates, which is based on PV/wind and diesel energy systems. A study has also been conducted on off-grid electricity generation with renewable energy technologies in India, which is based on the technical and economic aspects [20]. The techno-economic feasibility study of autonomous hybrid wind/PV/battery power system for a household in Urumqi China is discussed in [21]. A techno-economic evaluation of various hybrid electrical power systems has also been discussed [22]; the authors laid emphasis on rural telecom system. The paper investigates the technical, economic and environmental performance of the various hybrid energy configurations.

The design and economic analysis of an off-grid photovoltaic system for residential electrification is discussed in [23]. The authors compared the techno-economic design of PV systems with those of conventional energy systems. The techno-economic assessment of an off-grid PV-powered community kitchen for developing regions is also presented in [24]. The goal of this paper is to investigate the economic and environmental implications of the PV design. The environmental analysis is based on the life cycle emissions evaluation of the PV/battery system. The technical and economic design of photovoltaic and battery energy systems are discussed in [25], with the central aim of investigating the technical feasibility and economic benefit of the PV/battery design. Weniger et al. presents the sizing of residential photovoltaic/battery systems [26], with strong emphasis on the strategy to design cost-optimal solutions.

These studies provide a good background for further research in the aspect of community-based energy solutions for developing countries. Apart from the techno-economic framework on which these contributions are based, some of the papers also examine the social aspect in light of the load requirements/profiles of the intended energy consumers. In addition, some others consider it from the perspective of the socio-economic advantage of the electricity system (i.e. the well-being of the users in the long-term). Such considerations are part of the social features that are important for planning and developing off-grid energy systems.

However, in our previous paper [4], we report a solar PV energy system that is based on socio-technical and economic perspectives. This energy model includes a deeper social analysis, compared to the research published in [11–26]. This is because the community structure, current energy situation, users' life styles, behavioral tendencies and income, local conditions, users' perception, users' level of education, ascertaining whether or not the users will be willing to pay for the energy supply, capacity building in the installation and post-installation phases, finding out how the community will manage the proposed energy system etc., were adequately discussed in the study. We therefore use this social background as basis for proposing hybrid energy solutions (i.e. PV/diesel system) for the same community, i.e. Kutunku, Gwagwalada, Abuja Nigeria. While it is expected that there would be a difference between the techno-economic analyses of the single-source and the hybrid energy solutions, the social characteristics remain the same for the intended community.

The development of energy system entails a reasonable understanding and evaluation of the social characteristics, which then informs the technical solutions for the community [4]. Because there is no global standard, methodology or tool for analyzing the social characteristics, unlike the techno-economic aspect, the social backgrounds or viewpoints differ from one location or community to another. This is why the information about the community and the intended users becomes crucial for proposing the localized energy solutions. Some of the papers in [11–26] also paid particular attention to the environmental performance of the technical solutions, which also serves as good background for analyzing the extent to which carbon emissions are being minimized by utilizing clean energy technologies.

This paper proposes the development of a hybrid energy supply system (HESS) for a small community of 24 houses, based on the s ocio-technical–economical approach. It aims to take our previous study in [4] some steps further. Previously, we have presented a single-source electricity system based on solar photovoltaic technology, for electrifying the community for 24 h per day over the year. Due to high solar irradiation cycle of the Kutunku community during the long dry season, the system can adequately meet the total demand of the consumers. However, load reduction becomes unavoidable during the short rainy season to manage the available electricity from the PV power plant. This limits the operation of certain appliances, especially the fridges in the houses. Our intention in this new study is to address this issue by introducing a diesel generator system to the existing PV model to develop the HESS, thus, supporting the users' total demand during the dry and the rainy seasons. The generator is introduced to serve as a back-up for the PV plant; this way, the comfort of the users will be ensured during the two seasons. The HESS is modeled with DIgSILENT PowerFactory software according to the architectural plan of the community. Different methodologies and tools have been employed by the authors in the literature [11–26] to realize their various research goals, but our approach is based on the global engineering standards such as the IEC standards 62257-7, 62257-4, 62257-2, 62257-9-1 [27–30], and the IEEE standards 1562, 1561 and 1661 [31–35], and field experience. This approach is based on worst-case scenario, i.e. highest users' demand and lowest peak sun hours.

The real-life outputs of solar photovoltaic systems are lower than the standard test condition (STC) values. This is because of ambient temperature, incomplete utilization of solar irradiation and inefficiency of the balance of system (BOS) that lead to losses [4,5,31,36]. We obtain design safety factors (D_{sf}) for different PV array sizes, which are used to quantify the energy losses that need to be compensated for. These factors help in determining suitable solar photovoltaic capacities that can support the users' worst-case demand, at the same time compensating for the total losses. Solar photovoltaic energy losses were not analyzed in [11,13,15–17]; we therefore fill this gap by assessing the performance of the PV system in terms of power output, energy production, yield and losses and efficiency.