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Multi-year techno-economic assessment of proposed zero-emission hybrid community microgrid in Nigeria using HOMER

O.A. Odetoye [a], P.K. Olulope [a,*], O.M. Olanrewaju [a], A.O. Alimi [a], O.G. Igbinosa [a]

[a] *Department of Electrical and Information Engineering, Landmark University Omu-Aran, Kwara State, Nigeria*

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ABSTRACT

This paper presents a novel use of the HOMER Software for the multi-year economic, environmental, and energetic assessment of a proposed multi-source standalone renewable microgrid. A rural-but-rapidly-commercializing community in Nigeria's middle belt was used as a case study, with an average power demand of 975 kW and average consumption of 23.028 MWh/day. A generation mix of flat-plate photovoltaic (PV) array (3 MW nominal), concentrated solar thermal (CSP, 9 MW nominal), and small hydropower (SH, up to 200 kW), with battery storage (200 strings), system converter (2.5 MW nominal) using the Oshin River was recommended as the optimal system for minimizing the cost of electricity (LCOE) in HOMER. A diesel-based system was also simulated and a multiyear analysis for a 25-year period shows that the Net Present Cost (NPC) of $55.7 million for the renewable microgrid is vastly superior to the $408 million for the diesel microgrid, with LCOE of $0.26 and $1.01 per kWh respectively. The system also saved up to 7540 metric tons of CO2 per year in emissions. The results of the study indicate the proposed microgrid as an economically and environmentally superior alternative to diesel generators in the long term, and as deserving consideration for similar applications.

1. Introduction

ENERGY is nature's currency for all activities [1]. From the motions and metamorphoses of the galaxies in space and time to the reactions that take place within the smallest cells in the human body to create and sustain life, energy is involved in all physical processes. Economical activities rely on the timely and adequate provision of energy with which to carry them out [2]. Of the different forms in which energy is harnessed and utilized by man, electricity presents the most versatile [3]. Electrical energy continues to garner a rapidly-increasing number of available applications, and much of the technology that is essential to modern society relies on it. For these reasons, there is a well-known correlation between electricity access and productivity in twenty-first-century economies [4,5].

Due to several factors such as global warming, climate change, and international political events and trends, the importance of renewable energy in modern society is a major theme of the global conversation on environmental and technological sustainability [6,7]. The displacement of fossil fuels by renewable technologies in power generation systems is a prominent theme of discourse in the world's developed countries. In this sense, in such climes, renewable energy is usually considered primarily for its environmental sustainability merits, with generation adequacy and potential economic benefits being secondary motivators [8]. Yet, of equal importance is the provision of access to clean and economically-sustainable supplies of electricity in places where electricity is not yet

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[*] Corresponding author.
E-mail address: olulope.paul@lmu.edu.ng (P.K. Olulope).

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available, such as numerous regions in developing countries [9–11]. Nigeria, for example, has barely over two-thirds of its population having access to grid electricity, not counting those who are connected to the grid but have inadequate supply [6]. Of the proportion of the Nigerian population that does not currently have grid access, rural communities are disproportionately represented [12]. Thus, efforts towards industrialization and commercial activity in these communities tend to necessitate reliance on local alternatives to grid power, especially fossil fuel generators. In Nigeria, diesel is a commonly-used fuel for this purpose, especially for capacities beyond 10kVA. Thus, not only is there a globally-relevant need to transition to low-carbon electricity generation for the sake of the environment but also, in most developing countries, a pressing need to increase their electricity generation and delivery to tackle perennially-present energy deficits and enable competitive levels of economic productivity on the global scene. If new generation capacity is to be developed to make up for these often-massive deficits, in the twenty-first century, without increasine global fossil fuel emissions, it follows that large-scale development of renewable energy in such regions is needed.

Numerous strategies to reduce the impact of energy shortages, mostly by targeting and minimizing the wastage of energy on the consumption end, have been investigated [13–16]. Nevertheless, if the generation itself is inadequate, or the transmission capacity is insufficient (both of which are challenges found in the power systems of some developing nations), no combination of wastage mitigation and energy conservation strategies will be enough to prevent energy shortage in communities and its effects on their economy [17]. Despite the policies enacted by many developing countries, it is estimated that about 2 billion people have no electricity access [12], which is a major enabler of the entrenchment of poverty among citizens of such nations [18].

In Nigeria, many rural communities are on the path to citification in terms of both a growing population of individuals in the productive age bracket and also the increasing modernization of activity, including commerce. This is economically beneficial. However, an inadequate supply of grid electricity and the paucity of grid extensions of adequate capacity frequently hampers such community growth [5] or forces energy consumers in such communities to rely on local generation alternatives such as diesel generators where it can be afforded. Apart from the economic strain that this presents, the use of diesel and gasoline-based systems for locally generating electricity causes health hazards to millions of citizens and inhabitants of the nation [19].

It is already well-established that small and medium-scale systemization of renewable technologies such as solar photovoltaic (PV), wind-driven generators, and mini- or micro-hydro systems and, where possible, pumped-hydro storage (PHS), is economically advantageous in several rural locations [20,21]. Furthermore, Nigeria has been identified as one of the most attractive opportunities for off-grid electrification on the African continent by the Rural Electrification Agency (REA) which is funded by the World Bank and the Federal Government of Nigeria. Feasibility studies by the REA to determine which renewable energy technologies would be most viable in various locations in the country showed that solar energy, both in PV form and concentrated solar power (CSP) form, is very promising for applications in most parts of the country and that their viability is higher in the northern regions [12]. Of these technologies, solar PV is the more common form in Nigeria, mainly used in solar home systems [6].

However, due to the intermittency of solar irradiation in Nigeria, a renewable energy microgrid based completely on solar PV would be unable to meet the energy demands of the consumers around the clock. In addition, the absence of rotating machines on the generation side tends to lead to a less-stable power system [22,23]. Hence, the improvement of the quality of service of such a microgrid by adding renewable sources with less intermittency or whose intermittency does not resonate with the daily cycle is of importance in renewable-only systems. Also, having a proportion of the power generation being contributed by rotating machines is desirable. This motivates the development of hybrid/multi-source microgrids in which combinations of solar photovoltaic with other technologies such as wind, small hydropower, CSP, and the addition of energy storage systems (ESSs). Such hybrid microgrid/mini-grid systems are also of higher reliability than single-source systems due to the decentralization of risk in the system [12].

The economic aspect of operating microgrids is very important, as it is one thing to prescribe and design renewable energy systems, and it is another matter to develop and operate them economically, with competitively low costs compared to non-renewable energy systems. Despite the well-publicized benefits of renewable energy, in many community or public projects, the choice of a renewable system over a fossil-fuel generating system depends mainly on the overall costs. Thus, economic analyses and design optimizations are important in such projects. In long-term analyses, two major indices of the cost-effectiveness of a renewable microgrid are the Net Present Cost (NPC), and the Levelized Cost of Electricity (LCOE). Obtaining this is in previous works has been done using several tools such as artificial-intelligence-based methods [24,25], special mathematical/numerical approaches and optimization algorithms [26,27], and specialized software [28], with the Hybrid Optimization of Multiple Energy Resources (HOMER) software being an example of the latter category and being used in this study.

The second section of this paper presents a review of relevant literature with an emphasis on important insights and the research gaps that justify this study. In the third section, a summary of the data sources, site location, and methods used in the work is presented. The fourth section presents an examination of the three operating scenarios considered in this study: storage-equipped renewable microgrid, diesel microgrid, and no-storage renewable microgrid. The fifth section presents the key measures, mathematical models, and indices used in the study, while the sixth section explains and discusses the results of the study. In the final section, conclusions and recommendations based on the study results are presented, as well as the challenges associated with the sudy.

2. Review of previous works

A number of authors have used the HOMER software as a tool for their hybrid system techno-economic analyses as well as the hybrid energy optimal designs. In Ref. [29], a study of a proposed on-grid system was conducted in a Colombian location, considering the three aspects of energetics, economics, and environmental impact. The research involved a mixture of wind and PV generation systems. Firstly, the researchers identified fertile locations for harnessing the aforementioned renewable resources in large quantities, then the locations were sorted by economic efficiency that could be expected from installations sited at each location, finally, the size of the solar arrays and wind farms were optimized in HOMER software. The research showed that the location with the most abundant resources was different from the location that could be harnessed at the least cost-energy ratio after a multi-objective optimization was carried out. Quantitatively, 441 PV arrays and 3 turbines were the optimal results for Colombia's Caribbean region, while the NPC was as low as $11.8 million and CO_2 emissions of the site were as low as 244.1 tons annually [29]. The project involved renewable proportions of up to 95%. Notably, while Colombia is not an African country, it is a tropical country like Nigeria.

In [30], the potential for a standalone hybrid mini-grid incorporating a waste-to-electricity biogas generation plant was considered for a site in Nigeria's capital city, Abuja. The system was modelled in HOMER and simulated using the average daily solar insolation for the city and the average daily production of solid waste for a PV-biogas hybrid project that also included a battery energy storage system (BESS). The researchers in Ref. [30] aimed at solving both an energy deficit and a waste management problem. The load profile of the city's research district was estimated from available data, the dispatch strategy was based on cycle charging (CC), and the researchers found that the hybrid system had the capacity to consistently meet the demands of the study location with an LCOE of $0.4128 per kWh. Furthermore, the hybrid system (with PV) was more economical compared to a biogas-only project which had an LCOE of $0.727 per kWh.

The authors in Ref. [31] investigated an exclusively-renewable microgrid system which was off-grid and incorporated hydrogen as an energy storage medium in tandem with a BESS in HOMER. Three separate operating scenarios of microgrid systems were selected and investigated to choose an optimal solution for an off-grid renewable-energy power-to-hydrogen-to-power system similar to the system in Ref. [32]. The first scenario involved a battery bank, the second scenario substituted the battery bank with a hydrogen tank and a fuel cell, while the third scenario contained both the hybrid hydrogen system and a smaller battery bank. All three scenarios had PV generation incorporated. The researchers in Ref. [31] found that the least LCOE of $0.342/kWh over 25 years came from the third scenario. However, the authors of [31] noted that the results are highly situation specific and especially dependent on the load profile.

In [33], an off-grid simulation of a microgrid with a BESS that is specifically used to supply the energy for a nocturnal street illumination system was carried out. The microgrid generation was solely from solar PV, with an installed peak capacity of 6.755 kW, which was installed on a campus system as opposed to an industrial, typical residential, or typical rural load as in Ref. [12]. The researchers in Ref. [33] investigated the gains that could be made from the system if the energy lost due to its asymmetric load profile could be fed into the grid, a consideration similar to the aforementioned observation of the authors in Ref. [31]. After incorporating a bidirectional power converter and grid-tying the system in HOMER, it was observed that the efficiency of the grid-tied microgrid was improved to about 140% of its value when it was operated in standalone mode. Thus, grid-tying the microgrid reduced energy losses [33].

It is often difficult to extend electricity macro-grids to island areas. For this reason, a standalone microgrid is frequently the most suitable and economical option. The researchers in Ref. [34] investigated a hybrid DC microgrid for an island in Greece. The system incorporated PV modules, wind turbines, as well as a hydrogen tank, fuel cell, electrolyzers, and BESS. Furthermore, the system was not only designed to supply electricity but also thermal loads such as the one described in Ref. [35]. The researchers in Ref. [34] found that the DC hybrid microgrid system was particularly economical compared to a diesel microgrid when the costs of transporting diesel to the island were considered. Furthermore, the generation from the wind turbine peaked in the winter months while the solar generation peaked in the summer months, which helped establish a complimentary operation of the various generators in the system.

In [36], the authors carried out modelling and optimization for an off-grid system situated in a rural area. The optimization of the microgrid was done in HOMER to reduce the NPC and LCOE of the system. The unmet load, as well as carbon emissions, were also variables which the study attempted to minimize. A genetic algorithm, similar to that described in Ref. [37], was also used to optimize the same set of variables, and a comparative analysis was performed between the genetic algorithm and the HOMER optimization. The researchers in Ref. [36] found the genetic algorithm to give a more optimal solution than HOMER for that specific study, which gave an LCOE of $0.163 for the system which contained wind generators, biogas, biomass, fuel cells, as well as a battery bank for a rural location in India.

In [38], various dispatch controls for an off-grid hybrid microgrid were evaluated. As in Ref. [34], an island location is considered for the study. However, in Ref. [38], an AC hybrid microgrid is considered as opposed to DC microgrid in Ref. [34]. The HOMER software was used to simulate and optimize a generation mix containing diesel generator, solar PV, BESS, and wind turbine using four separate dispatch strategies of load following (LF), cycle charging (CC), combined dispatch, and generator-order-based dispatch for the economic dispatch described in Ref. [39]. The simulation revealed that, in the case of the microgrid being considered, the load-following dispatch strategy gave the best LCOE and NPC over the course of a year compared to the other three [38]. However, the degradation and other multiyear effects were not incorporated in the models.

Similarly to Ref. [36], the research in Ref. [40] involved the analysis of the techno-economic prospects of an off-grid multi-source renewable energy microgrid. HOMER was used to determine the best configuration of the multiple sources in the system for a village community in India, where air pollution from fossil-fuel-driven generation is gaining attention [41]. Four combinations of the microgrid were considered, with the first combination having BESS, fuel cell, and solar PV while subsequent combinations had the fuel cell omitted, the BESS omitted, and then both the battery and fuel cell were omitted in the final configuration. The researchers in Ref. [40] found that including all three aforementioned components in addition to biogas, biomass, and wind generators, gave the minimum LCOE of 0.214$/kWh compared to other configurations considered.

The authors in Ref. [12] investigated the reliability of a possible off-grid system in Nigeria for a rural location using HOMER. The Loss of Load Probability (LOLP) as described in Ref. [18], of the system was obtained using a capacity outage probability table as 5.76×10^{-8} h per year, while the LCOE was obtained as $0.396 per kWh for a system consisting of a PV array and a BESS in conjunction with diesel generators. The authors in Ref. [42] also considered a Nigerian location in which solar PV, small hydropower, BESS, and a diesel generator were considered for a village. A genetic algorithm similar to that described in Ref. [36], as well as HOMER, was used to optimize the system component sizes and it was found that the correlation coefficient of 0.88 was obtained when both methods were compared, thus, HOMER and genetic algorithm for this purpose were cross-validated successfully.

In [43], the authors used HOMER to plan and analyze an on-grid microgrid concerning its economic performance. The microgrid contained a BESS and power generation was from solar PV. The solar irradiance, specifically, the global horizontal irradiance (GHI), was varied during the simulation, and the results showed an inverse relationship between irradiance and LCOE in the power system. Thus, the system was more economical with the incorporation of solar PV than without it, making a case for the grid-tying of microgrids as in Ref. [33]. A study on a standalone PV system with a BESS for an entire community versus an independent household in Rwanda showed that, for a single year, the household electrification was slightly cheaper than the entire community electrification per kWh [44].

Research work on a hybrid microgrid using a combined wind-and-tidal turbine system for an off-grid location was carried out and described in Ref. [45]. HOMER was used to optimize the generation mix given the sizes and costs of the turbine. However, as pointed out by the authors in Ref. [45], the construction and installation costs are not always accounted for in HOMER simulations, and that was the case for the aforementioned research work. In Ref. [46], a two-stage analysis was carried out for an off-grid microgrid in an Egyptian location. The said study concluded that the investment decisions for a PV-Wind-Battery microgrid are mostly controlled by the load growth and the BESS cost more than by the renewable resource availability.

The study in Ref. [47] describes the techno-economic analysis of a wind-PV-biomass system that was designed for a rural location in Pakistan using HOMER. The biomass potential of the location was characterized, similarly to Ref. [48], and used in the study with a cycle-charging dispatch strategy. After a sensitivity analysis, the microgrid, which was grid-tied, was shown to have an LCOE of 0.0574 $/kWh in a system that generates over 50 MW. In Ref. [49], a PV microgrid in Myanmar was investigated in terms of its LCOE (which gave 0.267$/kWh) and its carbon dioxide emissions saving was also about 374 tons annually. Furthermore, similar studies have been carried out in the Philippines, showing that systems incorporating both renewables and diesel can reduce costs compared to systems using only diesel for off-grid power generation.

A Bangladeshi study [50] considered an off-grid AC microgrid for a remote location. In the study, a PV-BESS system was evaluated in HOMER, and the study concluded that AC-coupled PV systems were more economical than DC-coupled ones. In Morocco, a study for a single house showed that a diesel-PV hybrid system with a BESS was more cost-effective than a purely PV-BESS system [51]. Another Pakistani study using HOMER revealed that grid-tied systems are better economically while off-grid systems are better environmentally when considering a hypothetical campus microgrid in Pakistan [52].

A study in Ref. [53] showed that in developing countries such as Nigeria, the use of renewable energy systems does not generally oppose the development of the economy, and can even be more beneficial for such countries than in developed countries. Another study on the feasibility of renewable energy systems involved the investigation presented in Ref. [54]. In the study, decision-making regarding renewable-based distributed generation systems was found to be most impacted by the research and development, more so in this regard than the cost associated with such systems. In Ref. [55], using a dynamic spatial dubin model, it was shown that the provision of technical aid in the development of energy systems in Sub-Saharan African countries creates a positive spatial spillover effect that, if properly managed, can help accelerate such development in the region. This set of studies shows that the feasibility of distributed systems in Africa is worth investigating further.

In Cameroon, a country on the eastern border of Nigeria, a PV-hydro system was considered for a rural community [56]. The LCOE of the system obtained in HOMER was $0.268/kWh. The study showed that the cost of energy storage, whereby the batteries had to be replaced at times, was the major expense in the system. In Ref. [57], three South Korean Islands were investigated for their off-grid microgrid potential. The authors of [57] reported that the simulations showed that the economic performance of off-grid renewable microgrids is sensitive to local physical and social factors. A Greek location was used as a case study in Ref. [58] for a 12-month period. The study showed that a diesel-PV hybrid system was better than a diesel-only system economically. However, the system would still have significant emissions. The study in Ref. [59], in addition to providing another set of Pakistani results, is written in the style that serves as a walkthrough that concisely documents the processes involved in using HOMER software. A dedicated review in Ref. [60] examines, in detail, the other published works on minigrids and microgrids in the West African enclave. These studies show that the economic performances of microgrids do not strictly follow general rules but that each case and location requires its own techno-economic analysis, and that HOMER software is suitable and extensively validated for performing such studies.

Some of the research gaps identified in the literature review of studies using HOMER, which this study is designed to address, are that no previously-known studies present (i) a multi-year analysis that accounts for load growth effects and equipment degradation (ii) an economically-competitive zero-emission community microgrid solution with an LPSP <0.001 (iii) a study involving solar thermal generation (iv) a simultaneous simulation of four renewable technologies in the microgrid yielding feasible solutions. Therefore, this study is the first of its kind in the mentioned respects.

3. Methodology

After the location for this study was chosen as Arandun, a town in Irepodun LGA, Kwara State, Nigeria, the long-term climatic (wind and solar) data for the location was obtained from the Prediction of Worldwide Energy Resources (POWER) dataset. For the hydropower component, the major river flowing through the location (the Osin/Oshin River) was stream-gauged at the driest and wettest points in the river's annual cycle. Afterwards, the monthly precipitation data for the location were used to estimate the average streamflows for the months of the year which were then used in HOMER. The load-profile data were obtained from the utility company. The other data used in the study include but are not limited to the price of diesel in Nigeria at the time of the research, the cost of the diesel generators, the fuel curve for the diesel generators, and greenhouse gas emissions rates.

A key reason for attempting to displace diesel with renewable energy in the study location is to reduce not only cost but also emissions, especially the toxic ones such as carbon monoxide which could arise from combustion. Millions of people die due to air pollution worldwide [49]. Furthermore, while the community is still a rural community, it is rapidly industrializing and agricultural activities are not the only activities being undertaken there, which is part of why a microgrid is recommended to aid the development of the community. Hence, the use of biomass in such a location could be hazardous to the health of the community. In addition, the water resources are such that while micro-hydro and CSP might be tolerated if carefully sited in the community, the use of electrolyzer and fuel cell in the proposed system could lead to water stresses as a fuel cell system of significant capacity would have an adverse impact due to existing uses of the rivers in the region.

The microgrid under consideration is initially designed to harness a mixture of solar PV, CSP, micro-hydro, and wind energy to find the optimal balance that can meet the load on a multiyear basis without being assisted by an external grid. CSP provides a degree of dispatchability by its nature. However, a BESS is also provided in the system using lithium-ion batteries to ensure that physically feasible solutions can be achieved in the HOMER simulation. Sensitivity variables used in the study include the head of the hydropower resource, as well as the discount (used to represent inflation effects) rate. Several input combinations and search spaces were defined and millions of scenarios were examined in multiple simulations, each of which took several hours to execute. Hence, for brevity, only those inputs which yielded feasible solutions were documented and compared in the results presented in this work. A diesel microgrid was also modelled and simulated, and the techno-economic performances were compared. The impact of removing the BESS from the system was also investigated. The scale and level of detail of the study, while being more than that of many previous works in the literature, was nevertheless constrained by the available computational resources, and more-detailed scenarios can be examined in future similar studies if more hardware resources are used. The researchers in this study used an Intel Core-i7 computer with 8 Gigabytes of RAM.

3.1. Novelty of the study

Apart from the fact that such a study has not been carried out in the location, most of the previous studies reviewed involved the implicit assumption economic conditions are stable over the lifetime of the project. However, this study does not make that assumption, and the multiyear analysis accounts for the projected effects of inflation on the running costs of the microgrid over its expected 25-year lifetime for more accurate results. The population of any Nigerian community is also going to grow if a microgrid that supplies power throughout the year is sited there, and the reflection of this in the load demand is accounted for in the multiyear analysis, which is a major novelty of this study. Also, a systematic review of existing uses of HOMER software has been provided.

Finally, HOMER does not have a CSP module but has a CPV one. This study is, from the literature review, the first to attempt to model CSP in a HOMER hybrid system, which was done by scaling the DNI data in Microsoft Excel to reflect the intrinsic thermal storage of CSP plants. This was achieved by rescaling the magnitude of the DNI for each hour, to spread the total monthly energy component across both day and night without increasing or decreasing the total energy yield. By this, the CPV is used to mimic the simplified realistic behaviour of CSP. Also, the differences between the physical efficiency of CPV and CSP are accounted for by reducing the efficiency in HOMER to 15%, which is deliberately conservative in order to introduce a safety factor into the results, compared to the values of >30% sometimes achieved in hot desert regions [61].

Fig. 1. Preliminary attempts at gauging the river head.

3.2. Site description

The experimental data was based on Arandun in Irepodun Local Government Area, Kwara State, Nigeria. The coordinates of the town are 8° 4′ 59″ N and 4° 57′ 0″ E, about 64 km distance (as the crow flies) from Ilorin, the state capital, within a few kilometres of the Osun-Kwara border. This location in Nigeria's middle belt situates it in the gateway region between the Northern and Southern Nigerian geopolitical zones. The town has a growing population of about 15,000 which peaks during the holiday periods and ebbs at other times of the year. The activities in the town are majorly agricultural and artisanal (which reflects a latent demand for electricity). Arandun has a number of rivers flowing through it, majorly the Oshin river described in Ref. [62], as well as other hydrological features, some of which are seasonal and some of which are perennial in nature. It lies in the tropical savannah of Nigeria and is possessed mineral resources such as tantalite, an ore of tantalum which is used in alloys [63]. Trading and small-scale local manufacturing, are heavily carried out in Arandun, and depending on the Government policies, it is likely to become a mining town in future for its tantalite deposits. The capacity of the community's existing connections to the national grid is low compared to the demand which leads to overloading, and due to the location and difficulty of maintaining the transmission network in that region, the town experiences long periods of outages which leads to reliance on local generators for the most part, for those who can afford it. As a result, the town has a significant number of electricity consumers that are not connected to the grid and rely solely on local generation. This leads to noise, air pollution, and high costs of business. Furthermore, commercial activities, especially in such a developing community, are highly vulnerable to periods of fuel scarcity in Nigeria. For these reasons, a displacement of the fossil-fuel generators by non-combustive renewables is a need of the community. Fig. 1 shows a photograph of preliminary attempts at gauging the Oshin River used for hydropower in the study where it flows through Arandun, at its driest point in the year (in February).

3.3. Climatic conditions

Arandun is geographically located in the southern reaches of Nigeria's tropical savanna climatic belt. It experiences two annual seasons, the wet/rainy season that peaks around July (summertime in the northern hemisphere outside the tropics), and the dry/harmattan season that peaks around January (wintertime in the northern hemisphere outside the tropics). Total annual rainfall between 700 and 2600 mm is usually observed, which feeds the rivers in the community.

3.4. Load data

Many studies that are conducted with HOMER Pro software tend to use the prepackaged/default load profile in the software while external data is used only for energy resources [42,64–66]. However, in this study, the additional step was taken that the load profile of the selected location was investigated and a.

data-based model was developed in Microsoft excel. The qualitative data and expected patterns were gathered both by visual inspection and observation to determine the nature and capacity of the power system on which the community currently relies, the migration pattern of the Arandun community influencing their population and electricity demand at various times of the year, as well as the transformers and their ratings. Monthly, hourly, and weekly load profile data for the community was obtained from the Transmission Company of Nigeria (TCN) records, scaled, and used to model the community load in HOMER. Fig. 2 shows the monthly peak load in Megawatts for the Arandun Community for 2020 and 2021. From the figure, it is evident that the higher peak loads are recorded in the harmattan season compared to the rainy season. Fig. 3 shows the total energy consumption in the same period, and it is evident that the harmattan months also have more energy usage compared to the rainy months. This makes sense because the harmattan months would require more expenditure of electricity for illumination and pumping of water. The fact that the end-of-year holiday periods (at which time the population of the community is likely to be at their annual peak) are also in the harmattan season is also relevant in justifying the shape of the graph in Fig. 3. This is desirable, as it means that the load is less when there is less solar energy (i.e in the rainy season).

The hourly-load profile was gathered for a few days in the harmattan Season and averaged. The same step was done for the rainy

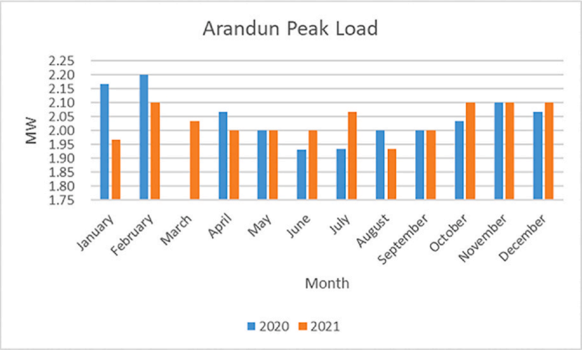


Fig. 2. Peak load in Megawatts for the Arandun Community.

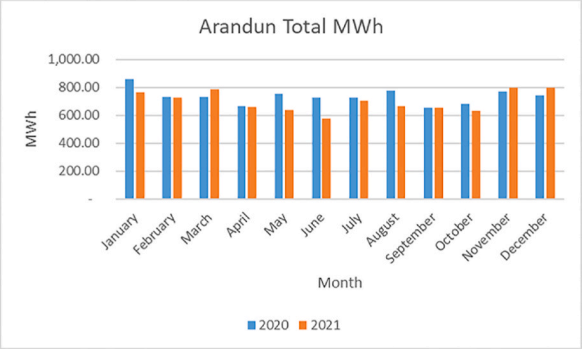


Fig. 3. Monthly energy consumption in MWh.

season. By this method, two seasonal load profiles were generated: May (rainy season), and November/December (harmattan). The system experienced fewer blackouts in these periods, hence the choice of these periods for a more accurate estimation of load demands for developing the seasonal hourly load profiles. Figs. 4 and 5 show the hourly load profiles for May and November/December. December is a holiday month, while November is a typical harmattan month, hence, days selected from both were chosen to develop a single harmattan profile.

The average load for the community as evaluated using HOMER after all interpolations and approximations were carried out was 975 kW, with an absolute annual peak demand of 2216.8 kW. The HOMER-estimated daily energy usage for the year 2021 was 23,400 kWh per day while the real average daily consumption for the community was calculated as 23,028 kWh per day, which validates the model closely enough and.

shows an outstanding accuracy with 98.3% agreement between the software prediction based on given data and built-in algorithms, and real-world calculations for 2021, considering the quality and relatively low quantity of data available. This also justifies why HOMER is suitable for this study. A box-and-whisker plot of the monthly energy usage profile as estimated by HOMER is provided in Fig. 6. The box-and-whisper plot illustrates the interquartile ranges of the load consumption in the community for each month For an annual overview of load patterns, a histogram showing the relative frequency of various energy usage levels is also provided in Fig. 7 which is not a symmetric normal distribution as might be expected according to Ref. [67], but more similar in shape to a right-skewed normal distribution. This also agrees with what can be inferred from Fig. 6, and shows that the system rarely operates near its peak load.

3.4.1. Renewable resource data

Both primary and secondary data were used in this study. The primary data were the streamflow measurements for the Oshin River, which was gauged at its February (minimum/harmattan) and June (maximum/rainy season) levels, and then other months were interpolated linearly using the precipitation data for the location. The monthly average streamflows are the input data which HOMER uses for its hydropower potential calculations. The research in Ref. [68] estimates the Oshin river head as being about 7 m when measured at another town along the course of the river. The authors in Ref. [62] mentioned that there exists a 2 m weir/dam on the river already. However, primary measurements in this study show a conservative available head of 3–5 m, which is explainable by the aforementioned facts. The head was measured using the hose-level method described in Ref. [69], while the velocity and streamflow were measured using the indirect method described in the same work. Fig. 8 shows the streamflow data used in the study, measured on site at Arandun. The streamflow is, as expected, high during the rainy months and at its lowest (but not zero, as the river is not seasonal) during the driest harmattan months. There are other rivers in the region. However, the Oshin is chosen in this study because

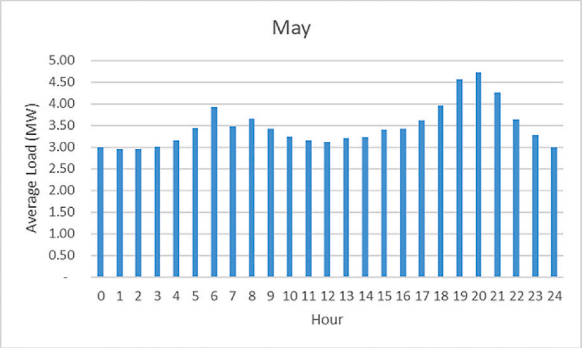


Fig. 4. Hourly load profile for rainy season.

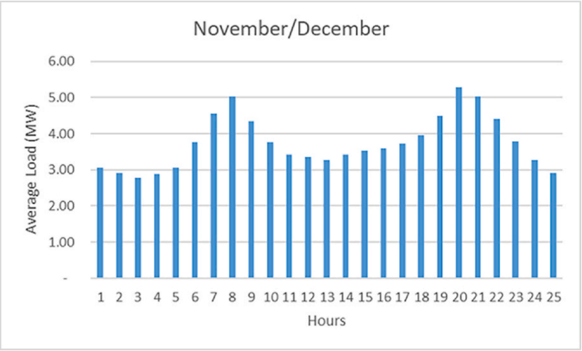


Fig. 5. Hourly load profile for harmattan season.

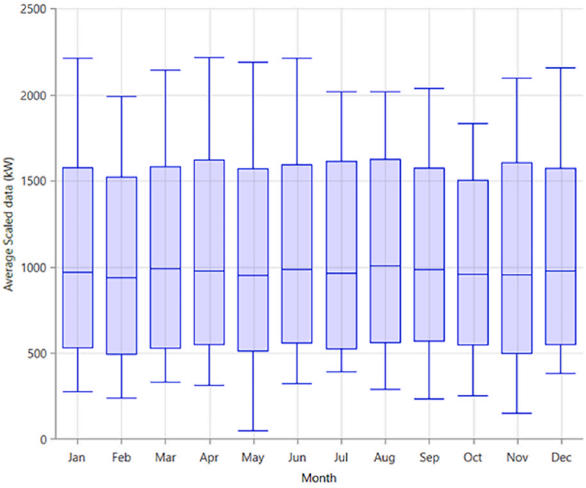


Fig. 6. Box-and-whisker plots Summarizing monthly load profiles.

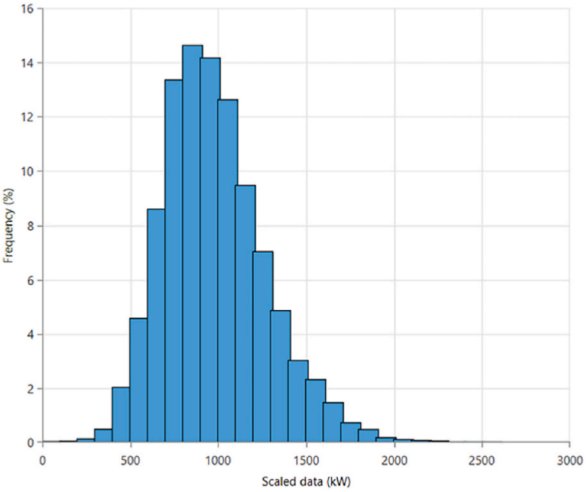


Fig. 7. Relative frequency histogram of load demands.

it has already been identified by previous works such as [68] as having hydropower potential.

The secondary data obtained in the study were obtained from the NASA Surface Meteorology and Solar Energy Database which is frequently used in such studies with HOMER. These data were the monthly average Global Horizontal Irradiance (GHI) wind speed,

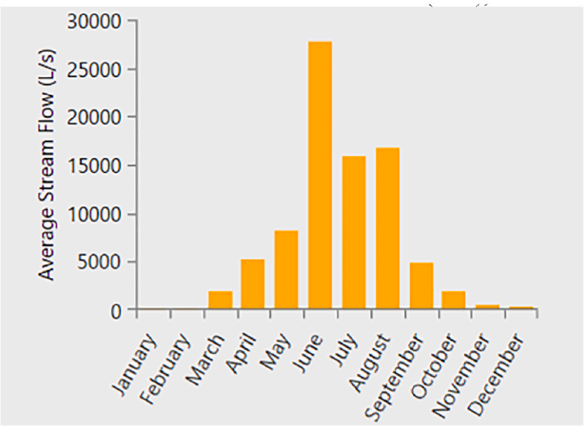


Fig. 8. Scaled average monthly streamflow for oshin river.

and temperature data for a 22-year period, as well as the Direct Normal Irradiance (DNI), which was.

similarly obtained from the POWER dataset [70]. Fig. 9 shows the GHI data as used in the study, while Fig. 10 shows the DNI data and Fig. 11 shows the wind data used. GHI and DNI data are used for PV calculations while CSP (represented in HOMER as a scaled-down and less-intermittent version of the inbuilt CPV module) is calculated using only DNI. The DNI data was scaled and stretched in the daily cycle to reflect the thermal inertia of CSP working fluids.

4. Operating scenarios

Three Scenarios are considered for the microgrid: renewable microgrid with BESS, diesel microgrid, and renewable microgrid without BESS.

4.1. Renewable microgrid with BESS

The renewable microgrid configuration is shown in Fig. 12. The combination of renewables in the presence of chemical energy storage was investigated with solar PV, CSP, wind turbines, small hydro, and Lithium battery storage being considered. Due to the number of sensitivity variables originally considered, the system took over 3 h to simulate after the selective removal of several sensitivity variables. Hydro head based on physical survey and literature survey was estimated at 3 m and a case of zero discount and 10% nominal discount rate were also considered. 10 kW turbines were used as the base for wind, and 100 kW nominal ratings for hydropower were used as a base (for initial conditions and search space gradation). Dispatch strategies are rules which are used to determine how the generator and storage batteries behave when the renewable energy available is not enough to supply the load. HOMER has three dispatch strategies which are cycle charging, load following, and combined dispatch strategy which implements both depending on instantaneous system conditions and criteria. The dispatch strategies come into play when there is a capacity shortage and when both renewable and non-renewable generation are combined. In this case, however, the microgrid is purely supplied by renewable energy, and correspondingly, the selected dispatch strategies were found to have no effect on the performance of the microgrid.

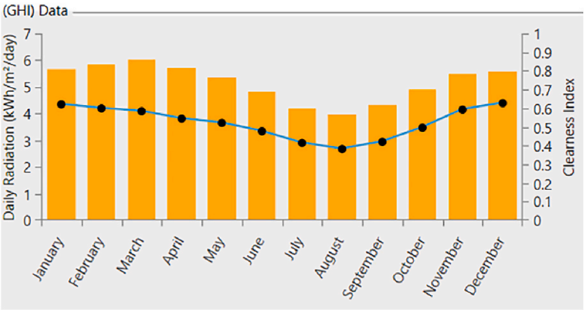


Fig. 9. Monthly average GHIs for arandun (from NASA).

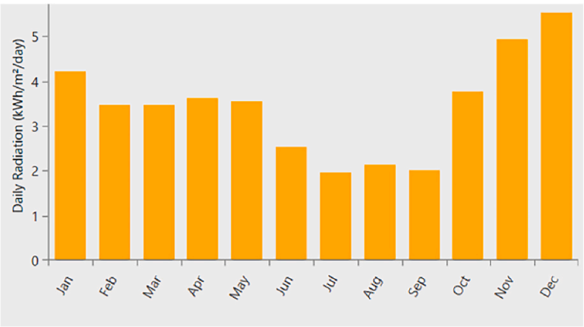


Fig. 10. Monthly average DNIs (from NASA).

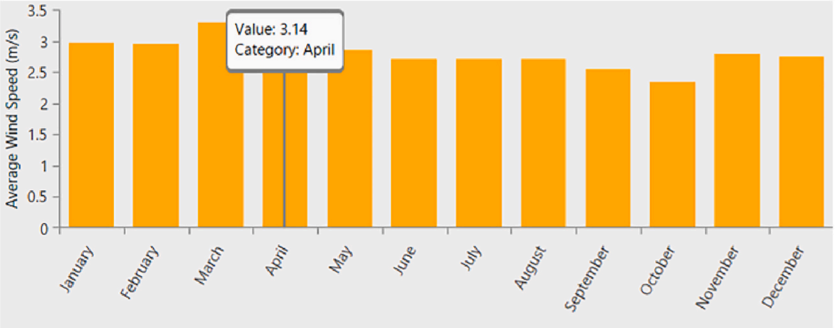


Fig. 11. Monthly average wind speeds (from NASA).

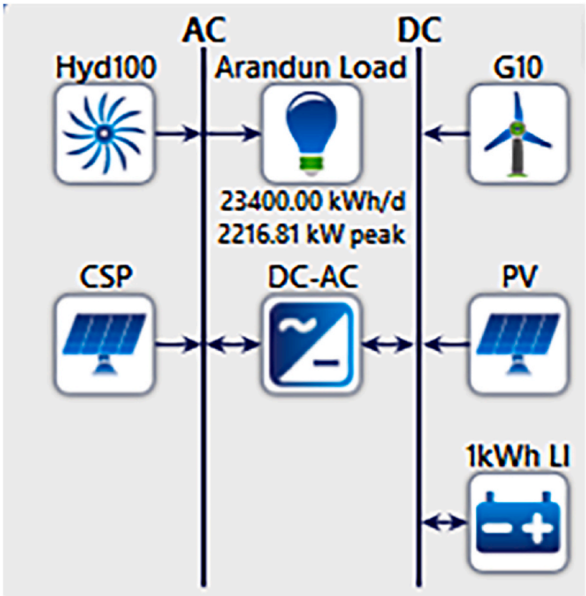


Fig. 12. Renewable microgrid Configuration with BESS.

4.2. *Diesel microgrid scenario*

The diesel microgrid scenario is used as a basis for comparison and cross-validation with the pure-renewable microgrid. Fig. 13 shows the condensed schematic in HOMER for the diesel microgrid scenario. To preserve the realistic outlook of the analysis, the flexible sizing option using both diesel and renewable sources (which is fairly common in literature especially) was passed over in

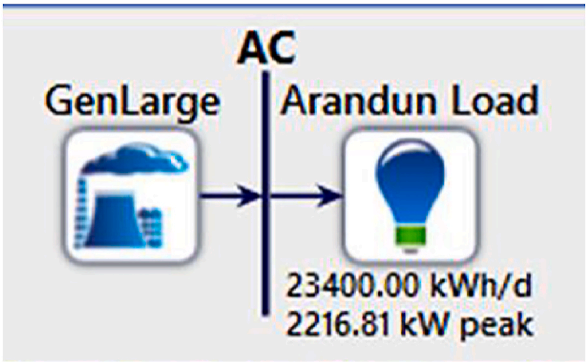


Fig. 13. Diesel microgrid Configuration in HOMER.

favour of sizing in discrete units according to specifications of real generating sets commonly used in Nigeria. Prices of diesel generating sets were obtained from online marketplaces, and where necessary, by direct correspondence with distributors and manufacturers. The cost of diesel as obtained around the same time by the market survey was ₦700, corresponding to about $1.69. Being a general-purpose microgrid, a power factor of 0.8 lagging was used for conversion between kVA and kW, as HOMER works only with the latter (HOMER works with energy and its time derivatives such as power). Large diesel generating sets are a dispatchable resource, and this was also implemented in HOMER, hence, there was no need to include a BESS in the diesel microgrid case. An inflation rate of 10% annually was used in the study. The battery and solar equipment batteries were obtained from battery vendors, PV array statistics, and CSP statistics from literature respectively, and levelized so that the cost of batteries in the simulation was realistic. $144/kWh of Li-ion storage was used in the study.

4.3. Renewable microgrid without BESS

Since CSP has intrinsic energy storage capability, the performance of a no-BESS system with the CSP generation was investigated, especially the cost savings and the impact on the availability of the electricity supply in the microgrid. The schematic for this system is shown in Fig. 14.

5. Key measures, models, and indices

The following are the relevant indices for evaluating the microgrid performances in the study.

5.1. Net present cost (NPC)

The Total Net Present Cost for a power generating station is the sum total of its life-cycle costs. It corresponds to the present value of all expenditures for installing and operating the system components over the lifespan of the project (in this case, 25 years), less the present value of all revenues earned during that time. It is not defined by any single equation but is a running calculation that shows the

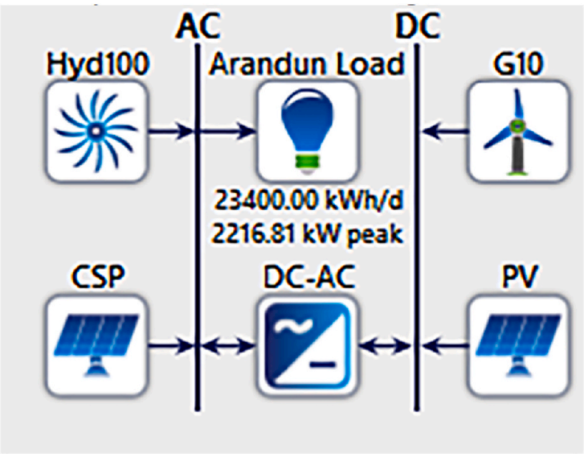


Fig. 14. Renewable microgrid Configuration without BESS.

economic performance over the lifetime of the project.

5.2. Levelized Cost of Electricity (LCOE)

The Levelized Cost of Electricity (LCOE) for a power generating station is the average cost of generating 1 kWh of useful energy (i.e not counting losses) in the system over its lifetime. It is used to compare various options for electricity generation especially when viewed from the consumer perspective (it is scaled) while the Net Present Cost views the same phenomena from the investors' perspective (i.e it is an absolute value). Eq. (1) presents the standard formulation for calculating the Levelized COE as used in Ref. [43], modified for application in this study.

$$LCOE = (C_{at} - \dot{C}_b H_s) / E_s \tag{1}$$

Where: C_{at} is the total annualized system cost, H_s is the total thermal load served, C_b is the marginal cost of the boiler, and E_s is the total electric load served by the system.

However, there is no thermal load in this study, which only considers renewable and diesel-based electrical generation and demand as boiler-based systems have been avoided for the aforementioned reasons. Therefore, Eq. (1) reduces to Eq. (2) as follows.

$$LCOE = \frac{C_{at}}{E_s} \tag{2}$$

Eqs. (1) and (2) represent the indices used to compare the economic performances of the configurations of the microgrid.

5.3. Modelling of CSP generation

The mathematical modelling for PV and wind energy systems are common in microgrid literature, and also built into HOMER and is automatically implemented based on inputted solar GHI data. However, of notable interest is the mathematical model of the parabolic trough-type CSP plant based on salt as a working fluid, which is not natively implemented in HOMER prior to this work, and which is presented in Eqs. (3) and (4) [61].

CSP is a thermal technology while CPV is a photovoltaic technology. As HOMER does not natively support solar thermal generation, there were no previous studies that used HOMER involving CSP, which was intended in this study. The authors investigated HOMER's available models, model customization, and data entry options in HOMER carefully to design an alternative method. Before modifying HOMER's CPV model to mathematically mimic a CSP plant, the authors studied the mathematical models, modes of operations, and costs of both technologies. The authors successfully found a heuristic scheme to mimic CSP using HOMER's "CPV". This involved adjusting CPV parameters (such as efficiency) and also scaling and time-stretching the solar data for the location (using MS Excel) and then linking it with the "CPV" model in HOMER.

For example, in a real CPV, power generation stops when irradiation stops. However, the adjusted "CPV" model used in this study produces some output even at night, while maintaining the same daily and annual energy output that would be mathematically expected based on the actual irradiation data. This is the behaviour of a CSP plant. In other words, the CPV model in this case has been successfully customized and data processed so that power dispatch and cost performance are validated to mimic that of a CSP plant. This increased the complexity of the simulation and was one of the challenges in this study. No previous work in the surveyed literature documents such a successful attempt. The known limitations of this method are presented in a later section.

$$Q_u = F_R A_a \left[\frac{S - A_r}{A_a U_L (T_i - T_a)} \right] \tag{3}$$

In Eq. (3), Q_U is the useful heat gain for a concentrated collector, F_R is the collector heat removal factor, A_a is the area of the aperture of the solar concentrator, A_r is the area of the receiver, S is the solar radiation absorbed, U_L is the heat loss coefficient, T_i is the fluid inlet temperature, and T_a is the ambient temperature at the solar power plant location. Furthermore, the temperature obtained is given by:

$$T_o = T_i + \frac{Q_u}{mC_p} \tag{4}$$

In Eq. (4), T_o is the temperature of the working fluid at the outlet, m is the mass flow rate of the working (heat transfer) fluid, and C_p is the specific heat capacity of the heat transfer fluid.

The cost per kilowatt of the CPV plant in HOMER was increased to $3500/kW to reflect the high cost of CSP compared to photovoltaics ($3000/kW capacity in the study).

In modelling the thermal inertia of the CSP, the hourly DNI radiation data is aggregated and a daily average for each month is calculated by HOMER. Normally, it is this hourly average DNI (which varies by the hour) that is fed into HOMER for the CPV modelling in form of an Excel spreadsheet. However, in this study, it was necessary to ensure that while the total DNI radiant energy input per month is preserved for accuracy, the daily radiant energy input was spread out over all hours in the month equally. Therefore, the monthly radiant energy averages for the CPV plant were computed using an Excel file containing the original DNI data. A new hourly Excel spreadsheet was then prepared that distributed the total DNI irradiation (and thus energy output of the plant) equally over the hours in the month, iin such a way that the total energy would remain the same. The higher-order thermodynamics beyond those described are not considered in this study, as HOMER has no way to model these.

5.4. Loss of Power Supply Probability (LPSP)

Loss of Power Supply Probability is the likelihood that the combined generation from sources and storage cannot keep up with the load at any given time, leading to sub-optimal system performance [71]. The LPSP is computed using the time-series information of load and available power from all sources and storage, as outlined in a discussion and equation appearing in Ref. [72]. In a storage-equipped system not limited by converter capacity, LPSP can also be considered as the probability that the batteries state of charge (SOC) is below the acceptable level. HOMER calculates this value, however, the equation is presented in Eq. (5).

$$\mathrm{LPSP} = \Pr\{E_B(t) \le E_{Bmin}\} \tag{5}$$

In Eq. (5), Pr is a shorthand for probability, $E_B(t)$ is the energy in batteries at any time, $E_{Bmin}(t)$ is the minimum acceptable battery SOC.

6. RESULTS AND DISCUSSION OF THE TECHNO-ECONOMIC ANALYSES

Using the methodology, assumptions, mathematical models, and measures/indices described in the preceding sections, the study was carried out. A discussion of the results follows.

6.1. Renewable microgrid with BESS

Over 5 million solutions were simulated for this particular case. However, due to the unusual constraint faced by HOMER that the system was to be 100% renewable, over 60% of the simulated solutions were found to be infeasible either due to capacity shortage constraints or failing the multiyear adequacy test. It was generally found that wind energy installation was not recommendable in the chosen location due to the low availability of wind resources which meant that an unreasonably high number of turbines would have been needed. The chosen solution meets the demand completely while having a very competitive Net Present Cost compared to other solutions. CSP showed high viability due to its intrinsic thermal inertia as well. As expected in a tropical location relatively close to the equator, it was more highly recommended than solar PV according to the results of the simulation (see Table 1).

The total NPC for the renewable microgrid with battery storage was calculated as $55,724,760.00 while the levelized COE was calculated as $0.26 for each unit of electricity generated. The chosen optimal system has a system architecture and capacities for each technology as shown in Table I. Wind energy in the location was found to be suboptimal, hence the results of the feasibility survey discourage the use of wind turbines in the microgrid project unless cost is not assumed to be a priority. Even in such a scenario, the amount of space that would be taken up by any significant wind installations makes land use a hard constraint against the en-masse installation of wind turbines in the area. Table II shows a breakdown of the total NPC for the renewable microgrid. The optimal solution for the system gave a photovoltaic array consisting of 3000 kW of photovoltaic generation capacity, a 9 MW capacity concentrating solar plant, as well as 200 strings of 50 6V batteries of 1 kWh each (or 167 Ah). Table III shows a selection of component costs based on April 2022 data. The cost prices were obtained mostly by direct correspondence with vendors, while the operating costs are assumed that there are no component breakdowns outside the scheduled maintenance and replacement periods, as well as the estimated derating factors (see Table 3) (see Table 4) (see Table 2).

The battery energy storage as designed is based on Lithium-ion technology. Lithium batteries are less vulnerable to degradation over time, and they tend to charge faster than lead-acid batteries. The search space for the battery capacity to be put in the microgrid includes 0, 200, and 500. The search space was originally more fine-grained. However, the complexity of simulations made it necessary to selectively eliminate some entries in the search space which had already proved themselves to be invisible. For this reason, the simulation had to be repeated with various search spaces. Because there are 10000 batteries needed, space considerations are also important. Table IV presents information on the battery energy storage system recommended after the optimization. The LPSP of this renewable microgrid equipped with a BESS is low, as the simulations yield an NPC that already accounts for replacement costs. The LPSP in this case is 1.87×10^{-5}% (see Table 5).

6.2. Diesel microgrid

For the diesel operating scenario, ultimately, 328 solutions were simulated in the final multiyear scenario run (for a 25-year lifetime project) after the search space was refined iteratively. 316 of the solutions were feasible while 12 were infeasible due to capacity

Table 1
ARCHITECTURE OF THE CHOSEN OPTIMAL RENEWABLE MICROGRID.

Component	Name	Size	Unit
PV	Generic flat plate PV	3000	kW
CSP	Concentrating Solar Power	9000	kW
BESS	Generic 1 kWh Li-Ion	200	Strings
Power Converter	System Converter	2500	kW
Hydroelectric	Generic Hydro 100 kW	23.5	kW

Table 2
Net present costs breakdown of the renewable microgrid.

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Concentrating PV	$31.5 M	$2.25 M	$27.0 M	-$20.3 M	$0.00	$40.5 M
Generic 1 kWh Li-Ion	$1.80 M	$2.50 M	$1.44 M	-$1.08 M	$0.00	$4.66 M
Generic flat plate PV	$9.00 M	$750,000	$0.00	$0.00	$0.00	$9.75 M
Generic Hydro 100 kW	$459,845	$344,875	$0.00	-$114,962	$0.00	$689,759
System Converter	$75,000	$0.00	$75,000	-$25,000	$0.00	$125,000
System	$42.8 M	$5.84 M	$28.5 M	-$21.5 M	$0.00	$55.7 M

Table 3
Selected Component costs used at Study Time.

Name	Capital	Replacement	Operations and Maintenance
CSP per kW	$3500	$3000	$10
1 kWh Li-Ion Battery	$180	$144	$10
PV Panels (Averaged)	$3000/kW	$3000/kW	$10
Generic Hydro 100 kW	$459,845	$344,875	$13,795
Mikano Diesel Genset (500kVA)	$81,238.22	$81,238.22	$1.69/Litre of diesel
Mikano Diesel Genset (100kVA)	$25,973.68	$25,973.68	$1.69/Litre of diesel

Table 4
Design properties of the battery energy storage system.

Quantity	Value	Units
Batteries	10,000	qty.
String Size	50.0	batteries
Strings in Parallel	200	strings
Bus Voltage	300	V
Average Energy Cost	0	$/kWh
Energy In	222,624	kWh/yr
Energy Out	199,413	kWh/yr
Storage Depletion	−1000	kWh/yr
Losses	22,211	kWh/yr
Autonomy	8.21	hr
Storage Wear Cost	0.0506	$/kWh
Nominal Capacity	10,000	kWh
Useable Nominal Capacity	8000	kWh

shortage constraints. In the optimal solutions, 4000 kW of installed capacity was recommended by HOMER to meet up the load demand at all points during the microgrid lifetime, with an LPSP of 0.198%. This corresponded to a Net Present Cost (NPC) of $408 million despite having a capital cost of less than 1 million dollars initially. Further investigations showed that the effects of compounding inflation and fueling and maintenance expenses in an economic environment with dwindling relief of fossil fuel projects are responsible for the high ratio of running costs to initial costs. Illuminatingly, it is found that if the effects of inflation are removed and a discount of 20% on all products is introduced, the net present cost would only be $40.9 million, a tenth of its nominal NPC of $408 million under realistic economic conditions. This shows how much inflation and fueling costs greatly multiply the overall cost of the microgrid.

For comparative purposes, the system was also simulated with an assumption of zero inflation for the entire 25 years, with a discount of 20% on all expenses, which reduced the NPC to $40,911,500.00. This represents almost 10% of the original value under realistic conditions, due to the time value of money. This difference is due to the compounding of inflation (which HOMER represents by using the real discount rate instead of the nominal discount rate) in running costs over a period of 25 years while still giving the same results with less computational complexity. This is an accurate representation of the experience of running a fuel-based system in the long-term in Nigeria, and why renewable energy is fast gaining ground in the country with electricity users who can afford the high initial costs. The levelized COE for the diesel microgrid over the lifetime of the project was calculated as $1.01. Table V shows the electrical summary of the diesel microgrid in the first and last years of operation of the microgrid (see Table 6).

The diesel microgrid gives off emissions which increase with the amount of power needed from the microgrid. Hence, the microgrid will give off increasing amounts of diesel every year as the load grows. Table VI shows the annual emissions of various greenhouse by-products and pollutants in the first year while the plot in Fig. 15 shows the growth pattern of the emissions relative to the first year which is considered as 100%. As seen from the plot, by the end of the project lifetime, the emissions grow with the load and reach more than double the initial levels. This poses a high health risk to the people of the Arandun community in addition to contributing to ozone depletion and global warming. Further, such a power plant is liable to become a shutdown target of future attempts by the government to cut down on carbon emissions. This is also a reason why the renewable microgrid is chosen in this study (see Table 7).

Table 5
Electrical summary of the diesel microgrid results for the first and last years.

Quantity	Value in Year 1	Value in Year 25	Units
Electrical Production	9,636,755	26,521,943	kWh/yr
Mean Electrical Output	1102	3034	kW
Minimum Electrical Output	1000	1000	kW
Maximum Electrical Output	2217	4000	kW
Fuel Consumption	2,840,976	6,960,962	L
Specific Fuel Consumption	0.295	0.262	L/kWh
Fuel Energy Input	27,955,207	68,495,868	kWh/yr
Mean Electrical Efficiency	34.5	38.7	%
Hours of Operation	8743	8743	hrs/yr
Number of Starts	18.0	18.0	starts/yr
Operational Life	1.72	1.72	yr
Capacity Factor	27.5	75.7	%
Fixed Generation Cost	142	352	$/hr
Marginal Generation Cost	0.412	1.33	$/kWh

Table 6
Emission levels of pollutants in the first year of diesel microgrid.

Pollutant	Quantity	Unit
Carbon Dioxide	7,449,680	kg/yr
Carbon Monoxide	38,541	kg/yr
Unburned Hydrocarbons	2046	kg/yr
Particulate Matter	330	kg/yr
Sulfur Dioxide	18,210	kg/yr
Nitrogen Oxides	7387	kg/yr

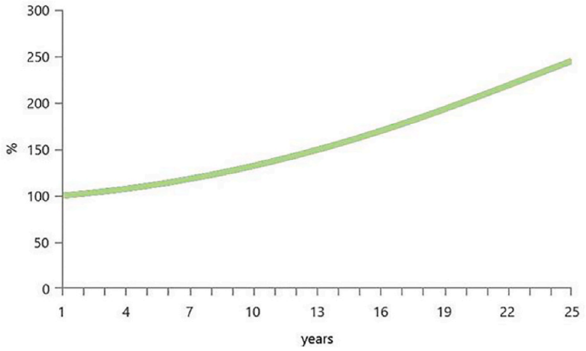


Fig. 15. Evolution of emissions over the system lifespan.

Table 7
Comparison with other West African Studies.

Location	Configuration	LCOE ($/kWh)	Study
Lade-II, Nigeria	PV/Diesel/BESS	0.396	[12]
Itapaji, Nigeria	PV/Diesel/Hydro/BESS	0.267	[42]
Muyuka, Cameroon	PV/Hydro/BESS	0.628	[56]
Djado, Niger	PV/BESS	0.115	[74]
Pategi, Nigeria	PV/Diesel/BESS	0.403	[75]
Elokato, Cote d'Ivoire	PV/Diesel/Hydro/BESS	0.203	[76]
Ajasse-Ipo, Nigeria	PV/Diesel/BESS	0.667	[77]
Kaduna, Nigeria	PV/Diesel/BESS	0.487	[78]
Fouay, Benin	PV/Diesel/BESS	0.207	[79]
Kudu, Nigeria	PV/Diesel/BESS	0.259	[80]
Djoundé, Cameroon	PV/Biogas/PHS	0.274	[73]
Arandun, Nigeria	PV/Hydro/CSP/BESS	0.261	*This study*
	Diesel	1.01	

Table VII presents a comparison of the LCOE results obtained in this study with those in other West African studies on microgrids. Eleven studies from Nigeria, its neighbouring countries (Cameroon, Niger, and Benin), and Cote d'Ivoire are presented and compared with the renewable microgrid in this study in terms of configuration and LCOE. The mean LCOE obtained in the 11 studies was $ 0.355, while the median LCOE was $ 0.274. The renewable microgrid LCOE of $ 0.261 obtained in this study is lower than both of these averages, and proves that the microgrid is economically competitive in the region in which it is located (West Africa). These studies [12,42,56,73–80] for validation were chosen for both their use of HOMER and the direct availability of the obtained LCOEs.

6.3. *Renewable microgrid without BESS*

The system was simulated without the BESS, and the results were observed. Notably, the generation had to be increased to compensate for the lack of storage. Even though the Concentrated Solar Power has intrinsic storage capacity, the 9 MW capacity of solar power was no longer enough to meet the load demand, with a new NPC of $67,314,760.00 being incurred (compared to $55.7 million with batteries) and still having an unmet electric load (LPSP) of 1.92% in the first year and a capacity shortage of 44% while wasting about a third of the generated electricity. Hence, the importance of implementing the BESS on the system performance and economics are established (i.e., the system with BESS that meets the requirements is more cost-effective than a no-BESS system).

The primary load and complementarity curves of the microgrid are shown in Figs. 16 and 17 respectively. The highest and concave curve represents the Concentrated Solar Power (CSP) output in kW which decreases during the middle months of the year (when precipitation interferes with the DNI component of solar radiation). The convex curve represents the output of the micro-hydro turbine over the course of the year in kW. The hydropower component produces its maximum of 200 kW from early June to late August, at which point it drops gradually until the next rainy season. The highly-erratic curve sandwiched between the CSP and the hydro represents the output of the inverter which is a combination of battery and PV system. The output of the inverter is used instead of the direct DC power output of the PV because it is a more accurate representation of the functioning of the system over time.

6.3.1. *Sensitively analysis*

A sensitively analysis is a common feature of studies done using HOMER, as it helps to illustrate how the system variables affects the overall performance of the microgrid. When there are only two variables, it is sometimes illuminating to examine the optimization curves. However, in this study, there are several variables, exceeding three dimensions. As such, the big picture of the sensitivity cases in HOMER are presented in Fig. 18, according to a pattern established in Refs. [56,76], and [80]. The height of the scroll bar on the rightmost part of the figure reflects the sheer number of scenarios considered in this study of which only a selection can be presented in the figure.

It is visible from the sensitivity analysis that most of the systems do not give a negligible LPSP like that of the chosen optimal

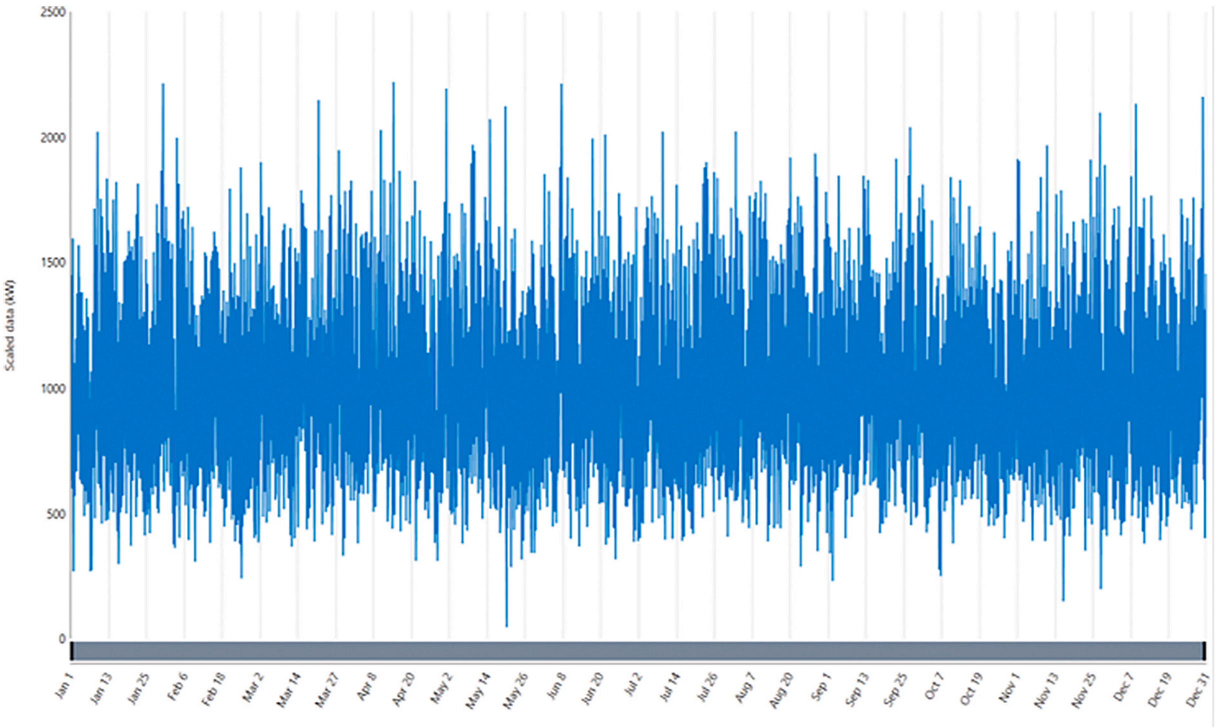


Fig. 16. Load curve for first year of system operation.

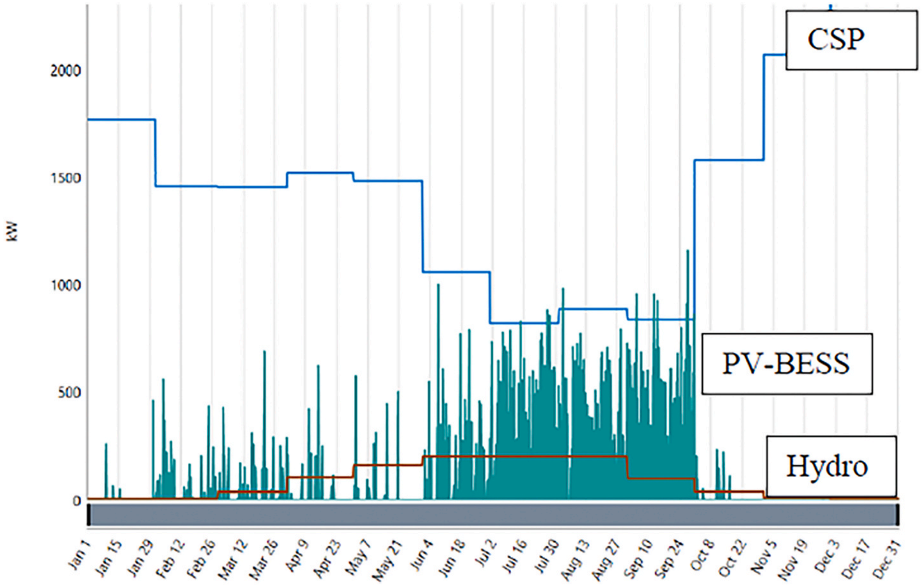
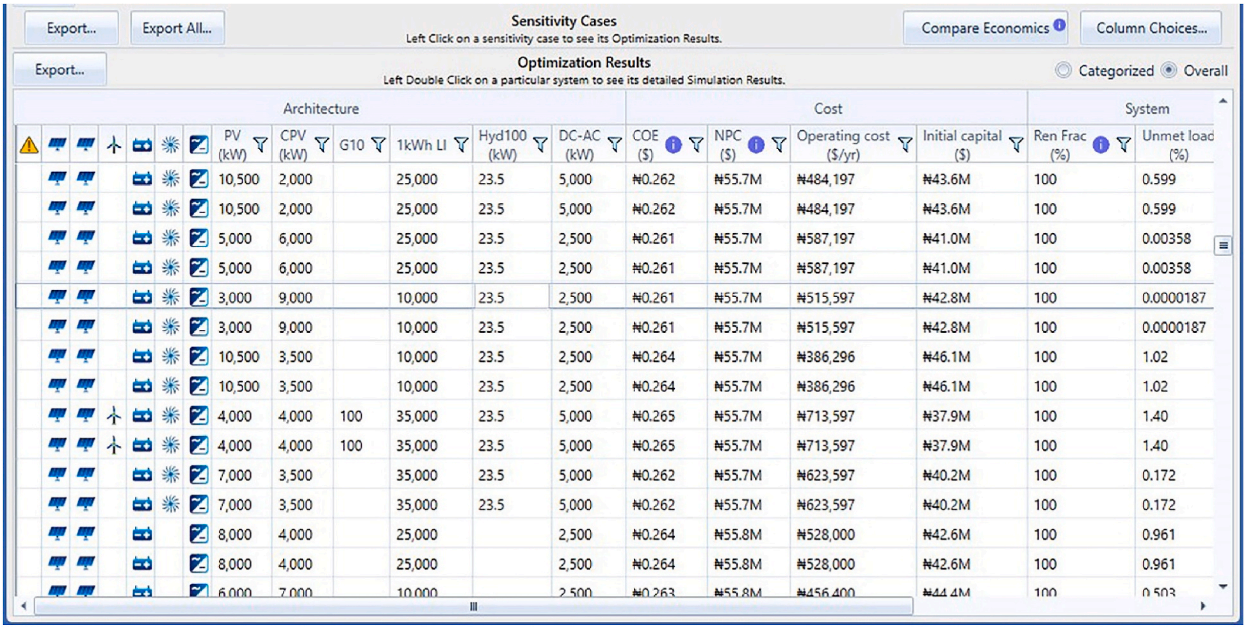


Fig. 17. System energy complementarity curve.



Sensitivity Cases
Left Click on a sensitivity case to see its Optimization Results.

Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

Architecture													Cost					System	
⚠							PV (kW)	CPV (kW)	G10	1kWh LI	Hyd100 (kW)	DC-AC (kW)	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Unmet load (%)
	✓	✓		✓	✓	✓	10,500	2,000		25,000	23.5	5,000	₦0.262	₦55.7M	₦484,197	₦43.6M	100	0.599
	✓	✓		✓	✓	✓	10,500	2,000		25,000	23.5	5,000	₦0.262	₦55.7M	₦484,197	₦43.6M	100	0.599
	✓	✓		✓	✓	✓	5,000	6,000		25,000	23.5	2,500	₦0.261	₦55.7M	₦587,197	₦41.0M	100	0.00358
	✓	✓		✓	✓	✓	5,000	6,000		25,000	23.5	2,500	₦0.261	₦55.7M	₦587,197	₦41.0M	100	0.00358
	✓	✓		✓	✓	✓	3,000	9,000		10,000	23.5	2,500	₦0.261	₦55.7M	₦515,597	₦42.8M	100	0.0000187
	✓	✓		✓	✓	✓	3,000	9,000		10,000	23.5	2,500	₦0.261	₦55.7M	₦515,597	₦42.8M	100	0.0000187
	✓	✓		✓	✓	✓	10,500	3,500		10,000	23.5	2,500	₦0.264	₦55.7M	₦386,296	₦46.1M	100	1.02
	✓	✓		✓	✓	✓	10,500	3,500		10,000	23.5	2,500	₦0.264	₦55.7M	₦386,296	₦46.1M	100	1.02
	✓	✓	✓	✓	✓	✓	4,000	4,000	100	35,000	23.5	5,000	₦0.265	₦55.7M	₦713,597	₦37.9M	100	1.40
	✓	✓	✓	✓	✓	✓	4,000	4,000	100	35,000	23.5	5,000	₦0.265	₦55.7M	₦713,597	₦37.9M	100	1.40
	✓	✓		✓	✓	✓	7,000	3,500		35,000	23.5	5,000	₦0.262	₦55.7M	₦623,597	₦40.2M	100	0.172
	✓	✓		✓	✓	✓	7,000	3,500		35,000	23.5	5,000	₦0.262	₦55.7M	₦623,597	₦40.2M	100	0.172
	✓	✓		✓		✓	8,000	4,000		25,000		2,500	₦0.264	₦55.8M	₦528,000	₦42.6M	100	0.961
	✓	✓		✓		✓	8,000	4,000		25,000		2,500	₦0.264	₦55.8M	₦528,000	₦42.6M	100	0.961
	✓	✓		✓		✓	6,000	7,000		10,000		2,500	₦0.263	₦55.8M	₦456,400	₦44.4M	100	0.503

Fig. 18. System sensitivity cases.

system, as the unmet load calculated in HOMER is used to calculate the LPSP. It is also notable that the inclusion of wind turbine options significantly increases the operating cost, even when it does appear to have a competitive NPC. The LPSP of wind-inclusive options is not competitive. Also, the amount of noise that will be generated by dozens of wind turbine units and the way the land use scales up are not fully accounted for by HOMER simulations. When these are considered, it is clear that wind energy is not advised for this location.

7. Conclusion

Data was obtained by direct measurement, estimation, and from the trusted Prediction of Worldwide Energy Resources (POWER) dataset and pre-processed, cleaned, and fed into the HOMER Pro software for optimal selection of microgrid configuration. This exercise also involved economic information such as discount rate, inflation rate, as well as the cost of equipment and time value of money. The degradation of the equipment was also considered. The CSP did not have a direct model in HOMER, however, a suitable approximation was used which was the CPV since they are both DNI-dependent generation technology.

Renewable energy was compared with the diesel microgrid for the selected location and the renewable option was found to have a lower net present cost of $55.7 million compared to $408 million for the diesel microgrid, for a period of 25 years. Microgrid fulfilling zero unmet loads in the simulations while being cost-effective was a mixture of CSP, PV, and Micro-hydro in order of decreasing energy contributions. The hydropower resource selected was the Oshin River which is notable enough to have appeared in the academic literature previously. In addition to this, the emissions of the diesel microgrid were found to be astronomical compared to the clean alternative of the PV-CSP-Hydro-BESS renewable microgrid that was selected as the optimal solution. Wind energy was found to be economically infeasible due to low wind resources in the Arandun location. The complementarity of the various sources on the microgrid was also confirmed. Specifically, a renewable energy microgrid has the potential to be a more cost-effective energy solution than diesel generators in the community and should be looked into.

Wind energy was not found to be feasible on a large scale in Arandun in comparison to other renewable and non-renewable alternatives. Apart from the cost of the installation of wind technology that would be required, the number of wind turbines required to supply the demand would be infeasible to install in the amount of land available.

It emerges that Concentrated Solar Power is a promising option for generating solar power in the tropics as exemplified by the Arandun community. The proximity to the equator of Nigeria means that in areas with a long-enough dry season, the thermal storage ability of CSP may make it more viable than even solar PV in some instances. Further studies on the potential of a renewable microgrid in Arandun are required, especially considering the potential of other energy sources not considered in the study. Higher resolution data for the renewable resources should be gathered and the results of the study as compared to the NASA POWER database-driven results in this study.

7.1. Limitations, challenges and recommendations

As this is the first published study of its kind in more than one way, a number of previously undocumented observations, challenges, and recommendations emerged. The complexity of the HOMER model used for the zero-emission microgrid in this work proved difficult for the research workstation to manage in simulation, and the experiments carried out, while being on an unprecedented scale (for HOMER), were not of the scale originally envisaged by the researchers. It was found that the hardware requirements for simulation in HOMER increased exponentially with the number of variables and components in the grid models, especially when different technologies are combined. In this study, four renewable technologies were combined for the first time in a published HOMER-based work. The need to manually model CSP in this study arose due to HOMER not natively supporting solar thermal generation at the time of the study.

The consideration of higher-order thermodynamics in HOMER models of solar-thermal generation needs to be worked on. In this study, the thermal inertia has been mimicked on a first-order level by artificially shifting the radiation in a way as to ensure that the same total amount of energy that would have been generated in a CPV plant is generated, using the DNI data. However, the thermal effects of materials and details of solar field modelling have not been considered separately.

The optimization of the heuristic approach for mathematically simulating CSP with CPV can be looked into more deeply, to account for CSP-specific thermodynamic effects that may be relevant on faster time scales (but are too fast to matter in this study). Even better would be for future works to develop the implementation of native support for solar thermal generation in HOMER and other software applications of its class, such as PVsyst. Also, the ramifications and support frameworks necessary to implement such a study using an open-source application or code-based software (e.g. in Python, MATLAB, Octave) while retaining ease of use may be considered. The sensitivity analyses in this study would be a six-way study, as opposed to two- or three-way studies more commonly found in related literature involving HOMER. Standard and ways of representing the outcomes of such analyses may be investigated.

Also, in this work, some properties of the power electronics converters (such as heat management) were not in focus, and neither were social issues concerning land use for such projects in African communities. This could be looked into in future works. To accomplish any of these would require entirely new tools, or entirely new versions of existing tools to be developed, which is also a recommended area of study. More advanced reliability analyses could be performed on systems of this nature. Finally, how techno-economic prospects change over time and with respect to other factors such as location and time can be considered in future works.

Author contribution statement

Paul Kehinde Olulope, PhD; Oyinlolu Odetoye, M.Eng: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or

data; Wrote the paper.

Matthew Olanrewaju, M.Eng; Adeleke Alimi, M.Eng; OSARIEMEN Igbinosa, PhD: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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