Design and Analysis of a Photovoltaic-Battery- Methanol-Diesel power system

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Abstract

The utilization of renewable energy resources (RERs) in the traditional power system has gained a global recognition owing to their technical, economic and environmental benefits. The techno-economic analysis of a microgrid system that consists of diesel generator (DG), methanol generator (MG), photovoltaic (PV) and battery system (BS) is implemented in this study to evaluate the performance of the power system. The feasibility study of the power system is implemented by using HOMER application tool and meteorological data provided by the National Aeronautics and Space Administration. The analysis indicates that PV-DG-MG-BS microgrid system is the most optimized configuration based on the net present cost (NPC) of $213,405.4, cost of energy (COE) of $0.256/kWh, renewable fraction (RF) of 88.6%, diesel fuel of 3055 L/yr and DG operating hours of 1037 h/yr. The results obtained from the optimized configuration translate to a subtsanatial reduction in NPC, COE, diesel fuel and operating hours of DG when compared to the base case study. This indicates that the combination of DG, PV, MG and BS in a microgrid system is the most economical configuration to achieve a feasible result. Moreover, sensitivity analysis is carried out to investigate the impacts of solar radiation, load demand, fuel cost and inflation rate on the performance of the power system. The results obtained from the study clearly prove the effectiveness of using RERs to increase the sustainability and performance of the power system. This improves the standard of living and economic activities in areas where the microgrid systems are sited.

Keywords: Battery system, Cost of energy, Diesel generator, Microgrid system, Net present cost, Photovoltaic

1. INTRODUCTION

The sustainability of energy is one of the prerequisites for the socio-economic development of any nation. This indicates that the availability of the electricity at the load points is one of the performance indicators for building a strong economy on the global note [1]. Therefore, it is imperative to design a power system that effectively satisfies the consumers' power demand with a variety of complementary energy sources for human development and growth of commercial activities. The sudden increase in the global power consumption has been attributed to the high standard of living, population growth, urbanization and income growth [2]. As a measure to satisfy the electricity requirements of their citizens, many countries have resulted in the development of conventional power plants. On the other hand, the utilization of fossil fuels for power generation can cause global warming, acid rain, health challenges and greenhouse gas (GHG) emission [3]. The global energy consumption has been predicted to increase by 50% in 2050, with the bulk of the load demand coming from developing countries [4]. The uninterrupted power demand caused by the industrial revolution and digitization of many manufacturing companies has prompted the utilities to gradual change from the traditional power system to the microgrid systems with the smart-grid features and RERs [5]. The microgrid systems are designed to serve specific needs of consumers and offer several power solutions and service products for grid-connected and islanding systems. The proliferation of RERs in the traditional power system has become a promising solution to satisfy ever increasing load demand and gradual reduce the local consumption of already depleted fossil fuels. The utilization of RERs such as solar, wind, biomass and hydro power offers numerous techno-economic benefits and can improve access to sustainable energy supply in rural areas [6], [7].

The myriad utilization of RERs for power generation application has become a potential alternative to meet the global power demand [8]. Nevertheless, the design and deployment of RERs such as solar and wind resources have become a great challenging task for the microgrid operators (MGOs) owing to their intermittent and availability [9], [10]. The hybridization of the power system with multiple sources can assist the MGOs to overcome the intermittency of solar resources and maximize the efficiency of power supply and ensure the availability of electricity at all-time [11]. As a measure to optimally utilize the aforementioned resources, it is imperative to use multiple power sources in order to overcome the weakness and drawbacks of a single technology [12], [13]. This will help the MGOs to optimally utilize RERs and reduce the COE, NPC, GHG emissions and fuel consumption [14]. The power output of the PV system is a function of environmental factors such as irradiation and temperature, while biomass (methanol) is a sophisticated energy source that has been extensively utilized in the off-grid power system to meet the rural area's power demand. The application of methanol for power solution has an enormous potential in the present and future green technologies owing to the following advantages: improved safety, increased energy security, biodegradable and cleaner combustion. In the study, a microgrid system is designed with the combination of methanol and solar resources, this will make the proposed system to be technically and economically feasible. The utilization of the mixed energy will enable the MGOs to improve the efficiency of their power systems [15]. This enhances resilience of the power system, improves cyber security and brings economic value to society.

The global report indicates that 960 million people that translate to about 12.3% of the world population do not have access to electricity [16]. In view of this, most of the commercial and industrial activities depend on DGs that are not economically feasible and have a negative impact on the environment. Therefore, it is imperious to shift from brown energy technologies (BETs) to green energy technologies (GETs). According to renewable global status report of 2020, modern renewable energy and traditional biomass contributed 11% and 6.9% to the global electricity, while 79.9% and 2.2% came from nuclear and fossil fuels [17]. The high operating cost, emissions and fluctuation of fossil fuel prices have made the operation of the conventional power plants to be expensive and environmentally hazardous. These problems can be eliminated by using GETs based on their technical and economic benefits. RERs play a significant role to improve the power system sustainability, reduce global warming and health hazards [18]. This allows many consumers and independent power providers (IPPs) to produce their own electricity with the application of RERs irrespective of the locations at minimal operating costs. The utilization of RERs in the microgrid systems is a feasible solution considered by the government agencies for rural electrification projects and remote commercial buildings. The reduction in the costs of RERs due to rapid development of relevant technologies and government policies in terms of tax holiday, incentives and subsidies has encouraged the rural electrification with the application of RERs [19]. Owing to this, the best option is to invest heavily in the system that can meet the power demand as much as possible without incurring any additional cost for extending the utility grid to remote areas.

The hybridization of the traditional power system is relatively recent and few research works have been carried out on the optimization of the microgrid systems with the proliferation of the PV, DG, MG and BSS at design, planning and operational levels. Yahiaoui et al. [20] have utilized the particle swarm optimisation (PSO) algorithm to reduce the cost of a PV-DG-BS hybrid system, GHG pollutants produced by the DG and the loss of load probability. Wu et al. [21] have proposed the optimal energy management based on the heuristic control methods to reduce the fuel cost and obtain a cost-effective and reliable energy system. Ferreira et al. [22] have presented a generalized pattern search optimisation method for the determination of the optimal solution of economic and thermodynamic optimisation of a cogeneration system. Zhang et al. [23] have proposed a performance metric that is utilized to estimate emission, electricity price and service quality of islanding and grid-connected microgrid system. Aghaei et al. [24] have proposed a methodology assess the ideal task of a cogeneration microgrid system that comprises the BS, combined heat and power (CHP) unit and conventional thermal unit. Bracco et al. [25] have presented an optimisation model to reduce the CO_2 emissions and operating costs of a microgrid system that comprises of the gas turbines, PV and concentrating solar-powered systems. Izadbakhsh et al. [26] have presented a technique for the minimization of emission, the execution time and operating cost of a microgrid system.

The rural areas that are not connected to the utility grid owing to economics of scale and technical barriers that are related to their distances from the existing transmission and distribution (T&D) infrastructures, high terrains, low population density and low load demand [27]. The location of rural communities makes the extension of T&D systems to such areas to be economically and technically not feasible. This has obviously led to rural to urban migration on the global note owing to the absence of electricity in rural areas. This trend can be arrested by the provision of basic infrastructures in a sustainable manner to the rural dwellers [28]. This will improve the standard of living and reduce mass migration to the cities. The provision of the cost-effective electricity in rural areas can be achieved with the application of the standalone microgrid system. This research work is focused on designing of a PV-BS-DG-MG microgrid system based on techno-economic benefits of RERs. The selection of the PV and MG for the proposed power solution is based on the availability of methanol and solar radiation for the selected location with the annual average solar irradiation of 5.47 $kWh/m^2/day$ and annual average temperature of 24.25 ^oC. The deployment of only PV system in a microgrid system is not technically feasible owing to cloudy weather that is related to persistent rain fall, seasonal variation and shading effects that are associated with snow, trees and other items. This indicates that the operation of the PV can be complemented by the DG and MG. Hence, a combined operation of a microgrid system with a multiple resources is a cost-effective option to achieve a reliable power supply, fuel cost savings and reduction of emissions [29]. The research work presents a platform to compare the operation of a microgrid system in terms of economic and environmental indicators.

To the best knowledge of the authors, very few researcher works have taken into the consideration the sensitivity variation of some significant factors that are applicable to the operation of a microgrid system. The sensitivity analysis is carried out to investigate the effects of some parameters on the performance of the proposed power system. In addition to this, the application of methanol for the power generation application is very rare in the literature review. The outputs of this research work can be utilized by the government agencies as the standard to improve access to a reliable power supply, strengthen energy security and development of sustainable energy projects. The contributions of the study are listed as follows:

- ❖ To design an optimal model of DG-PV–MG-BS microgrid system that is best suited for meeting the load requirements when operated in an islanding mode.
- ❖ To conceptually design a microgrid system by taking RERs and their technical and economic characteristics into consideration.
- ❖ To carry out the sensitivity analysis of the proposed microgrid system by evaluating the effects of varying some parameters on COE and NPC.

- To assess the techno-economic benefits of the proposed microgrid system and compare it with the base case study.
- To analyze the suitability of RERS in combatting the global environmental pollution and improving the efficiency of the power system.

The rest of the paper is organized as follows: Section 2 presents motivation of the study, Section 3 discusses the structure of a microgrid system, Section 4 presents the techno-economic parameters of a microgrid system, Section 5 depicts various technical parameters of the power system, Section 6 presents the results and discussions, Section 7 presents the sensitivity analysis of the power system and Section 8 presents the summary and conclusions of the study.

2. MOTIVATION OF THE STUDY

The failure of the Nigerian government to meet the electricity obligation of its citizens has drastically reduced commercial and industrial activities in the country. The power sector was privatized to improve power generation capacity and to make the operation of the power system to be efficient. However, the privatization of the power sector has brought a lot of hardship to Nigerians and no important improvement in the power supply has been achieved based on the persistent load shedding and poor quality of power supply. It has been reported that 80% of the individuals that have access to electricity make use of DGs as a supplemental source of power supply. The persistent power outages in some parts of Nigeria owing to inadequate power infrastructures have led to annual economic loss that is estimated to be $29.3 billion [30]. Nigeria has a good potential of RERs such as wind, hydro power, solar and biomass. This has made the Nigerian Electricity Regulatory Commission to make a projection of a minimum 2,000MW of electrical power to be generated from untapped RERs. The potential of solar energy in Nigeria as shown in Fig. 1 is so enormous that 207,000GWh/yr of electrical energy production can be obtained if only 1% of Nigerian land area (923.768 km^2) were covered by the PV panels. The North West geopolitical zone of Nigeria with the land area of 216,065km^2 is the second largest zone in the country. The population of the aforementioned region is estimated to be 45 million people, out of which, only 14.6 million people have access to electrical power supply. The majority of un-electrified areas in the Kano-State are rural communities owing to the lack of rural electrification planning and execution model.

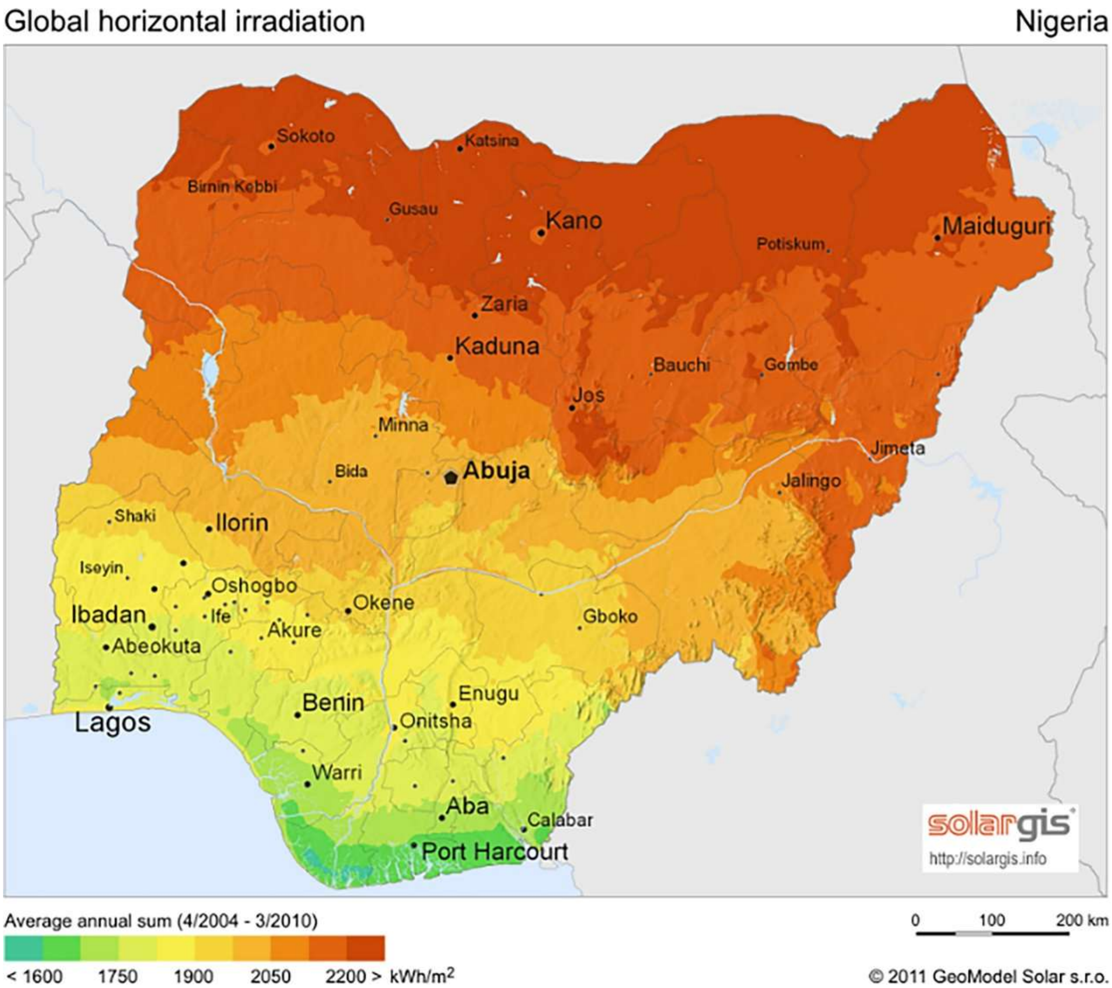

Fig. 1: The solar irradiation of Nigeria [31].

This research work is focused on the design of a DG-PV-BS-MG microgrid system for SMEs load points. The selected site for the study is Kano that is located in North West of Nigeria with the latitude $12^{\circ}0.1^{1}$N and longitude $8^{\circ}35.5^{1}$E. The geographical location of the site is presented in Fig. 2.

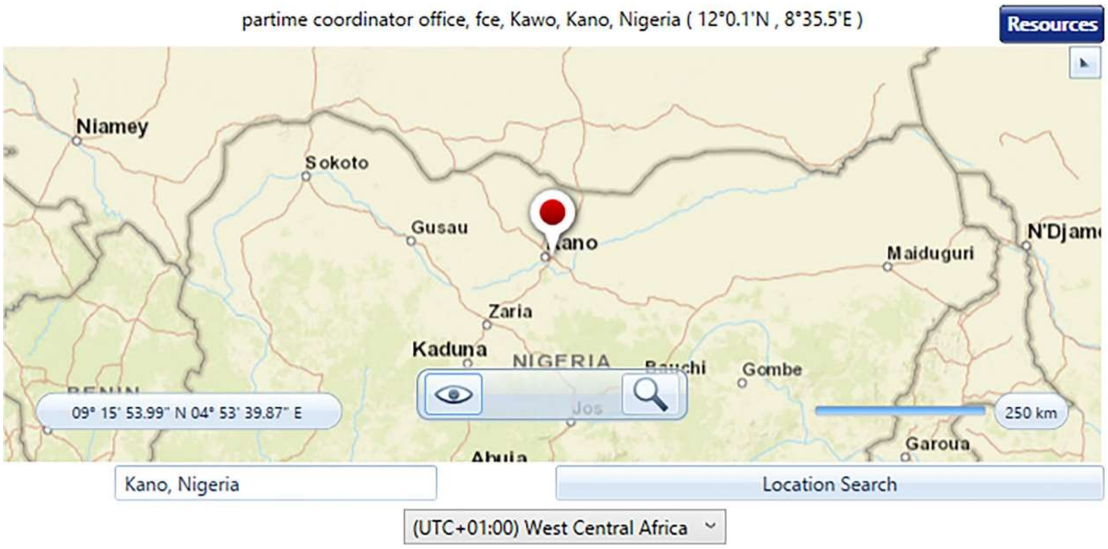

Fig. 2: Geographical location of Kano, Nigeria.

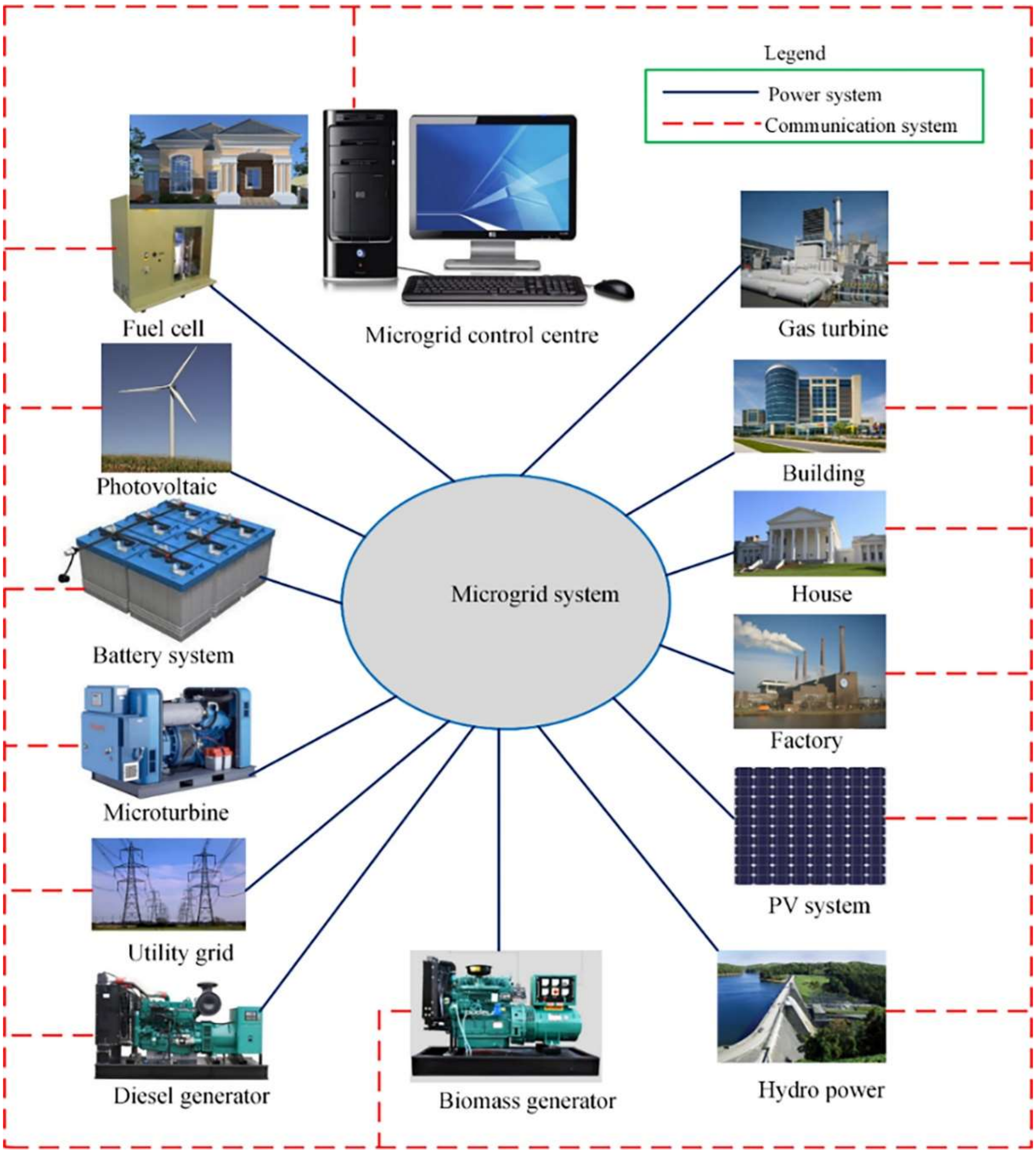

Fig. 3: Overview of a microgrid system with the basic components.

3. CONCEPT AND STRUCTURE OF A MICROGRID SYSTEM

A microgrid system consists of PV, wind system, DG, BS, hydropower, microturbines, biomass, fuel cells and dynamic loads. It is a localized system that is structured by the MGOs to operate in conjunction with or autonomy of the utility grid based on its automatic self-healing operations as shown in Fig. 3. The benefits of the microgrid systems extend to utilities and various communities, providing power solutions for the primary, secondary and tertiary sectors of the economy [32]. The mathematical models of the components of the proposed microgrid system are discussed as:

3.1 Diesel generator

The DG consists of a diesel engine and an alternator for generation of electrical power. It can be used for the continuous, prime and standby operations, grid support and peak shaving application. The DG is designed to operate effectively based on the availability of fuel and proper sizing of the DG. This is crucial for curtailment of load shedding and excess power generation [34]. However, high maintenance cost, high cost of fuel and GHG emissions have hindered the operation of the DGs for certain operations. The fuel consumption (F) of the DG is a function of electrical power output as shown in Fig. 4a. The F of the DG is presented in Eq. (1) as [33]:

$$F = F_o \times Y_{DG} + F_1 \times P_{DG} \tag{1}$$

where P_{DG} is the electrical output of the DG (kW), Y_{DG} is the rated capacity of the DG (kW), F_0 is the fuel curve intercept coefficient (units/hr/kW) and F_1 is the fuel curve slope (units/hr/kW) respectively.

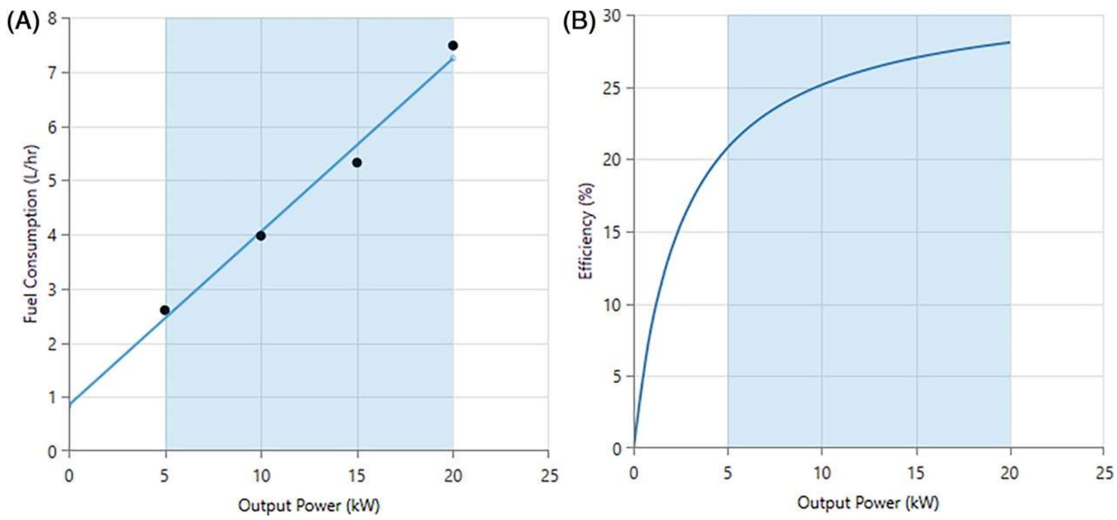

Fig. 4: (a) Fuel consumption of the DG and (b) Electrical efficiency of the DG.

The DG's electrical efficiency is a ratio of the electrical energy to chemical energy of the fuel as shown in Fig. 4b. The electrical efficiency of the DG is presented in Eq. (2) as [33]:

$$\eta_{DG} = \frac{3.6 \times P_{DG}}{m_f \times LHV_f} \tag{2}$$

where m_f is the mass flow rate of the fuel (kg/hr) and LHV_f is the lower heating value of the fuel (MJ/kg) respectively.

3.2 Photovoltaic system

The PV system converts solar radiation into electrical energy by utilizing the photovoltaic effect. Solar radiation is one of the prominent data that is essential for development of an effective solar energy conversion system and estimation of its power generation capacity [8]. The annual average solar radiation and a clearness index of the atmosphere for the selected site are found to be 5.47 kWh/m^2/day and 0.56. The average solar radiation and clearness index on a monthly basis are shown in Fig. 5a while Fig. 5b shows the monthly temperature of the selected site over a one-year period. The hourly power generated by the PV system can be calculated by utilizing the following equation [8], [33]:

$$P_{pv} = \left\{ PV_{Rated} \times PV_{DF} \left(\frac{I}{I_{STC}} \right) \left[1 + \alpha_p \left(T - T_{STC} \right) \right] \right\} \tag{3}$$

where PV_{rated} represents the rated capacity of the PV array (kW), PV_{DF} depicts the derating factor of the PV (%), I represents the solar radiation incident on the PV panel (kW/m^2), I_{STC} represents the incident radiation at standard test conditions (STC) (1 kW/m^2), T depicts the PV cell temperature (°C), T_{STC} represents the PV cell temperature at STC (°C) and α_p is the temperature coefficient of power (%/°C) respectively.

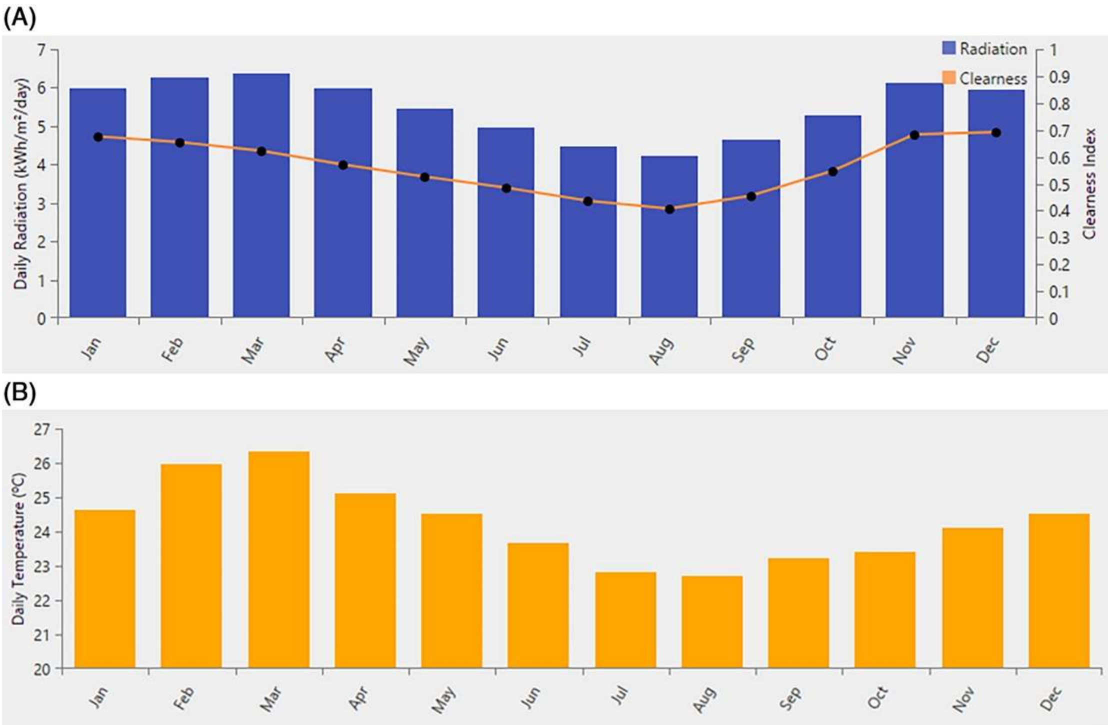

Fig. 5: (a) Average solar radiation and (b) Average daily temperature per year.

3.2.1 Clearness index

The clearness index is a dimensionless number that falls within the range of 0 to 1. It is the portion of the solar radiation that passed through the atmosphere to strike the Earth' surface. The clearness index can be expressed in Eq. (4) as [8]:

$$Clearmess_{index} = \frac{I_{av}}{I_{o,av}} \tag{4}$$

where I_{av} is the monthly average solar radiation (kWh/m^2/day) and $I_{o,av}$ is the extra-terrestrial horizontal radiation (kWh/m^2/day) respectively.

3.3 Battery system

The BS is an electrochemical device that can be used in the microgrid systems to overcome the intermittent nature of solar resources and enhances the availability of power supply. The BS acts as a storage medium to store the excess energy during the off peak period and releases the stored energy into the power systems during the peak load period when the output power of RERs is not sufficient to satisfy the load demand [14]. The output power of the BS can be estimated by using Eq. (5) [8].

$$P_{bs}^{\max} = \frac{N_{bs} V_{bs} I_{bs}^{\max}}{1000} \tag{5}$$

where N_{bs},, V_{bs} *and* $I_{bs}^{\max}$ denote the number of batteries, storage's nominal voltage (V) and storage's maximum charge current (A) respectively.

3.4 Methanol generator

The MG that is utilized in this study is driven by the methanol fuel produced from RERs such as biomass. The methanol fuel can be produced from biomass through a gasification process that is presented in Fig. 6. The annual power generated by the MG can be computed as follows [33]:

$$P_{MG} = P_{MG}^{\max} \times \beta_{cuf} \times 365 \tag{6}$$

where $P_{MG}^{\max}$ is the maximum rating of the MG and β_{cuf} is the capacity of utilization respectively.

The maximum rating of the MG can be estimated based on the availability of methanol from RERs as follows [33]:

$$P_{MG}^{\max} = \eta_{MG} \times \delta_{cv} \times M_{total} \times 1000 \tag{7}$$

where η_{MG} depicts the overall conversion efficiency of the MG, δ_{cv} denotes the calorific value of the methanol (MJ/kg) and M_{total} is the total methanol (ton/year) respectively.

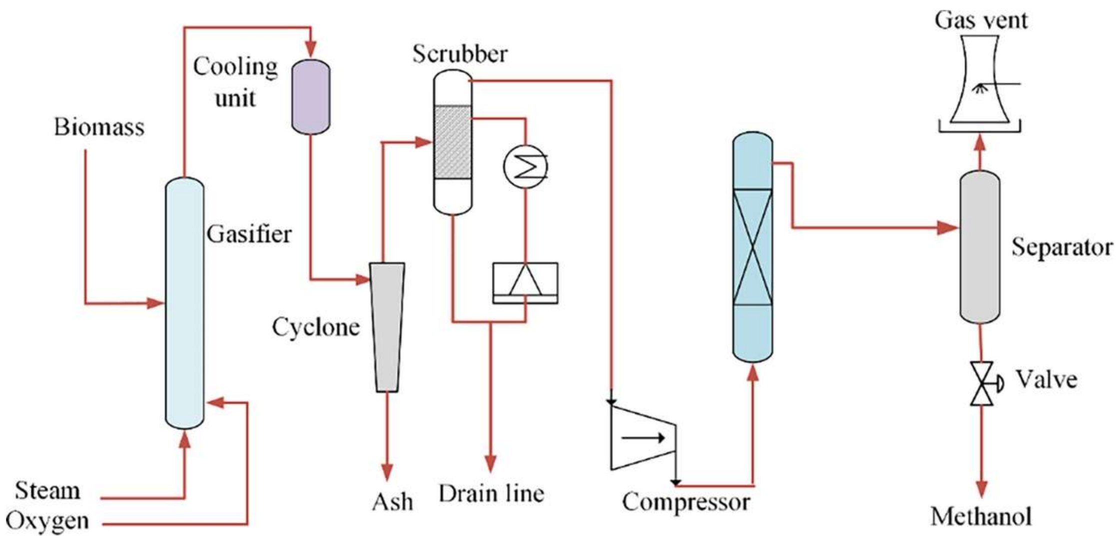

Fig. 6 Gasification and bio methanol synthesis system [34].

4. Techno-economic parameters of a microgrid system

The techno-economic analysis is carried out by the MGOs to obtain an optimal configuration with combination of various components of the power system [14]. The mathematical model that investigates the technical and economic impacts of RERs in a microgrid system is presented in this research work by using NPC, COE, annualized cost of the system (ACS), operating cost, return on investment (ROI) and internal rate of return (RIR).

4.1 Net present cost

The NPC of a power system depicts the present value of all the costs incur for installation and operation of the system over the lifespan of the project [14]. It does not include the present value of all the revenues that the microgrid operators earn over the lifetime of the project. The NPC is an important key performance indicator (KPI) by which it ranks the configurations of the system to obtain optimized results. This indicates that the NPC is the most economically preferable components that can be used for optimization of a microgrid system [8]. It is the basis on which the estimation of the total annual cost and the cost of energy is based. The NPC of the power system includes the operation and maintenance costs, fuel costs, capital costs, replacement costs and emission costs.

$$NPC = \frac{C_{ann,total}}{CRF(i, P_{proj})} \tag{8}$$

where i is the annual real interest rate (the discount rate), $C_{ann,total}$ is the ACS, P_{proj} is the lifespan of the project and $CRF(i, P_{proj})$ is the capital recovery factor respectively.

4.2 Capital recovery factor

The capital recovery factor is the ratio that can be used by the MGOs to calculate the present value of an annuity of a power project over a specified duration and discount rate. It is expressed in Eq. (9) as [32]:

$$CRF(i, P_{proj}) = \frac{i(1+i)^{P_{proj}}}{(1+i)^{P_{proj}} - 1} \quad (9)$$

4.3 Cost of Energy

The COE is the unit cost of producing 1 kWh of electricity from the power generating units. It can be expressed as [14]:

$$COE = \frac{C_{ann,total}}{ED_{served}} \quad (10)$$

where ED_{served} is the total electricity served (kWh/yr).

4.4 Total annualized cost of the system

The ACS is equal to the total NPC multiplied by the CRF. The total ACS of a microgrid system can be estimated by using the following equation [8]:

$$C_{ann,total} = CRF\left(i, P_{proj}\right) \times NPC_{total} \quad (11)$$

where NPC_{total} is the total net present cost ($).

4.5 Operating cost

The operating cost (C_{op}) is the annualized value of all cost and revenues other than the initial capital costs. It can be estimated by using the following equation [33]:

$$C_{op} = C_{ann,total} - C_{ann,capital} \quad (12)$$

where $C_{ann,capital}$ is the capital cost ($/yr).

4.6 Return on investment

The ROI is the metric utilized by the MGOs to compare the annual cost savings in proportion to the initial investment. It can be utilized to compare the returns from other investments and allow them to make the best management decision having measured and compared the performance of a number of investments [33].

$$ROI = \frac{\sum_{i=0}^{P_{proj}} \left(C_{na,ref} - C_{na,cs}\right)}{P_{proj}\left(C_{cap,cs} - C_{cap,ref}\right)} \quad (13)$$

where $C_{na,ref}$ is the nominal annual flow for base (reference) system, $C_{na,cs}$ is the nominal annual cash flow for current system, $C_{cap,cs}$ is the capital cost of the current system and $C_{cap,ref}$ is the capital cost of the base (reference) system respectively.

4.7 Internal rate of return

The IRR is an economic indicators used in the power system to evaluate the financial feasibility of any capital investment incurred during the upgrading of the existing power system or construction of a new power system [8].

$$0 = NPV = \sum_{t=1}^{n} \frac{C_t}{(1+IRR)^t} - C_o \quad (14)$$

where C_o represents the total initial investment cost, C_t depicts the net cash inflow during the period *t*, and t depicts the number of time periods respectively.

4.8 Renewable fraction

The RF is the portion of the electrical energy that originated from RERs and delivered to the load points [33].

$$RE_{fraction} = \frac{E_{served} - E_{non-renewable}}{E_{served}} \quad (15)$$

$E_{non\text{-}served}$ is the non-renewable electrical generation (kWh/yr) and E_{served} is the total electrical load served (kWh/yr) respectively.

5. HOMER SIMULATION TOOL

HOMER is an application tool that can assist the MGOs and IPPs to carry out techno-economic analysis of their power systems. The basic architecture of HOMER package is presented in Fig. 7. It is a novel tool that can be utilized to surmount many operational challenges that are associated with the complex characteristics of the power system and uncertainty of load growth as well as the escalation of fuel prices [8]. The assessment of the power system with the application of HOMER can be implemented by using the following principal tasks: simulation, optimization and sensitivity analysis.

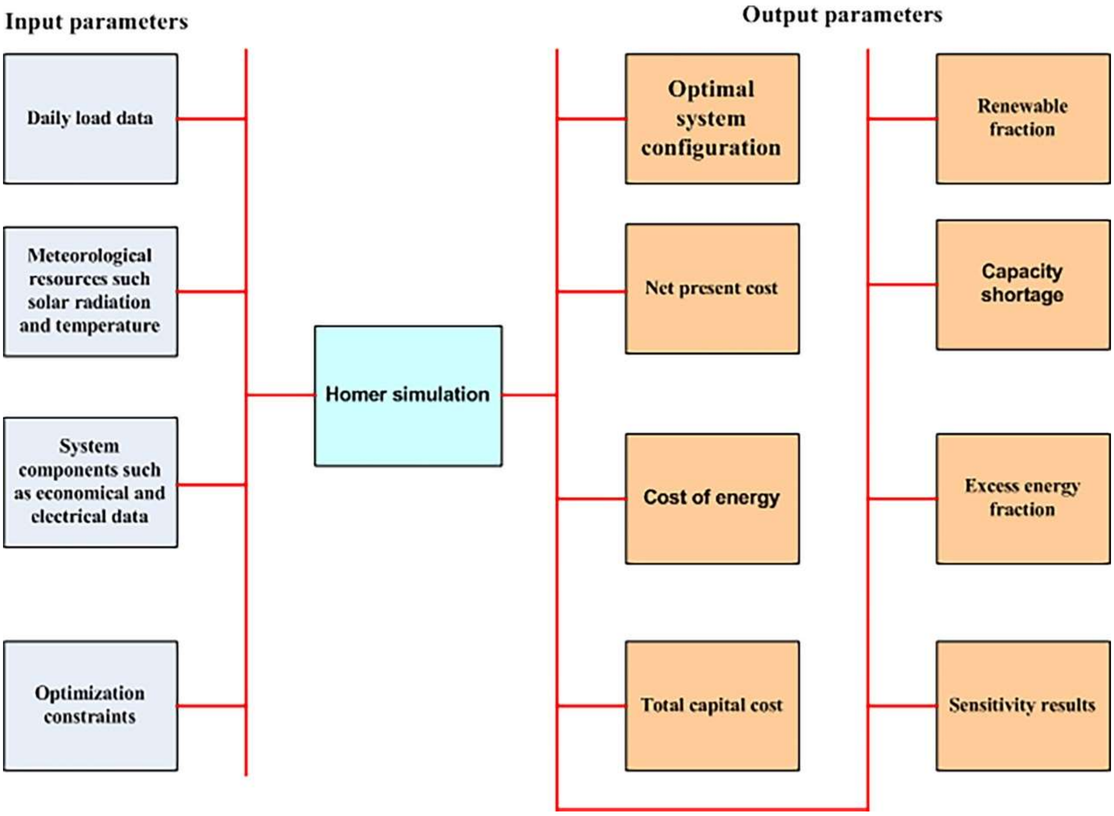

Fig. 7: Schematic diagram of HOMER application tool for optimization and simulation analysis.

6. TECHNICAL PARAMETERS OF THE PROPOSED MICROGRID SYSTEM

The microgrid system proposed in the study provides a combined operation of DG, MG, PV and BS that will yield numerous technical and economic benefits [32]. The proposed microgrid system can be used to overcome the problem that is associated with the climate changes and global warming and improve overall efficiency of the power system. The schematic diagram of a microgrid system with different components such as PV, DG, MG, BS and converter is presented in Fig. 8. A BS is used in the study as a backup to satisfy the load requirement. Moreover, the bidirectional converter allows the flow of electrical power from the DC bus to AC bus or vice versa. The excess energy can be stored with the application of the BS. The microgrid system proposed in the study provides a combined operation of DG, MG, PV and BS that will yield numerous technical and economic benefits such as low NPC and COE, fuel cost reduction, maintenance cost reduction, emission reduction, etc. The proposed microgrid system can also be used to overcome the problem that is associated with the climate changes and global warming, improve overall efficiency of the power system and ensure a continuous power supply without interruption. The parameters that are related to the operation of a microgrid system are defined in this section as a measure to implement feasibility analysis of the study. In view of this, all the critical components of the proposed microgrid system are considered for techno-economic analysis. The technical specifications of all the components of the proposed microgrid system as presented in Table 1 are used to obtain feasible solutions. The proposed microgrid system is designed by utilizing the nominal specifications and cost parameters of each component of the system as presented in Tables 1. The aforementioned nominal specifications and economic details as presented in Table 1 are used to evaluate the optimal operation of a power system and assess the economic feasibility of renewable energy technologies in a microgrid system.

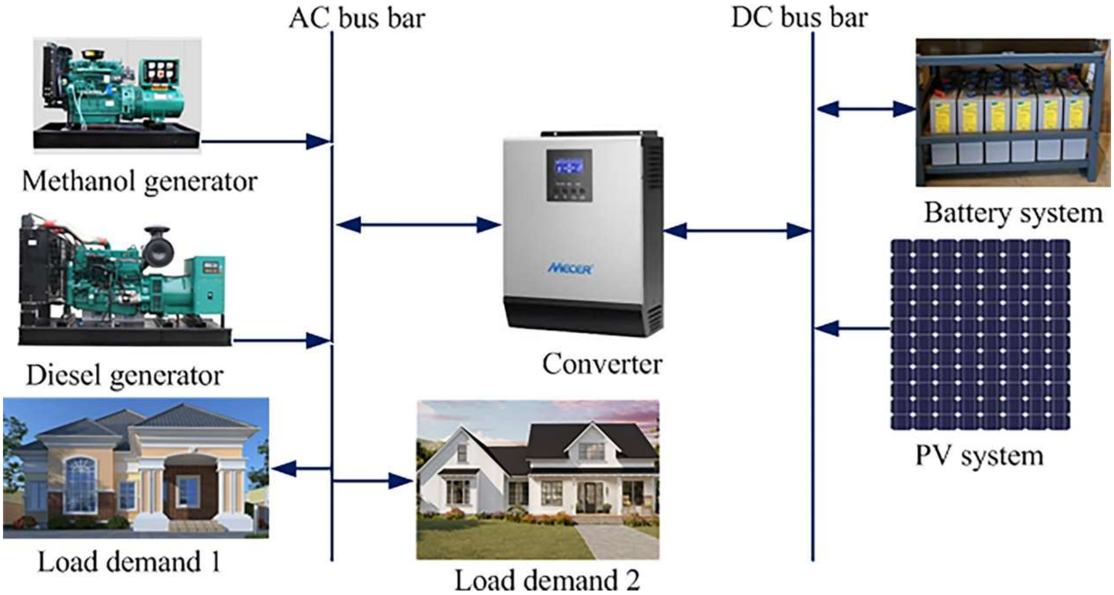

Fig. 8: Schematic diagram of a PV-DG-MG-BS microgrid system.

Table 1 Technical parameters of the proposed microgrid system.

Description	DG	MG	PV	BS	Inverter
Rated capacity	20 kW	1.5 kW	25 kW	Nominal capacity = 9.27 kWh and Maximum capacity = 4630 Ah	40 kW
Model number	Generac 20kW protector	Oorja 1.5 kW model T-3	Huawei SUN 2000 25 kW	BAE PVS 4940	System inverter
Capital ($)	2000	1200	3000	300	300
Replacement cost ($)	2000	1200	3000	300	300
O&M ($)	0.03 $/op.hr	0.01 $/op.hr	10$/yr	5 $/yr	5 $/yr
Lifetime	15,000 hr	10,000 hr	25 yr	15 yr	20 yr
Other technical parameters	Fuel cost = 1.2$L, Fuel cost slope = 0.32 L/hr/W, Fuel curve intercepted = 0.845 L/hr, Fuel properties Lower heating value = 43.3 MJ/kg, Density = 820 kg/m^3 , Carbon content= 88% and sulphur content = 0.4%	Fuel cost = 0.6/L, Fuel cost slope = 0.8 L/hr/kW Fuel properties Lower heating value = 20 MJ/kg, Density = 793 kg/m^3 , Carbon content= 52% and sulphur content = 0.33%	Derated factor = 96%, efficiency = 17.3%, operating temperature = 45 °C and Temperature coefficient = - 0.4100	Capacity ratio = 0.313, Rate constant = 0.995 (1/hr), Roundtrip efficiency = 85%, Max discharge current = 4440 A, Max charge current = 696 A, Max charge rate = 1A/Ah and Through = 9600 kWh.	Relative capacity = 100% and efficiency = 95%

6.1. Load profile

The power system is designed to satisfy the load requirements of small and medium sized enterprises (SMEs) with the peak load and average electricity of 20.46 kW and 165.44 kWh/day for load profile 1 and the peak load and average electricity of 2.32 kW and 11.25 kWh/day for load profile 2. In this research work, the load data is spread across 24 hrs horizon to obtain the load profile 1 and load profile 2. The load data is fed into HOMER application tool to produce the daily, montly and yearly load profiles as presented in Fig. 9 (a-c) and Fig. 10 (a-c). The daily load profiles 1 and 2 from January to December are presented in Fig. 9d and Fig. 10d where it can be deduced that the amount of electricity consumption varies from one month to another.

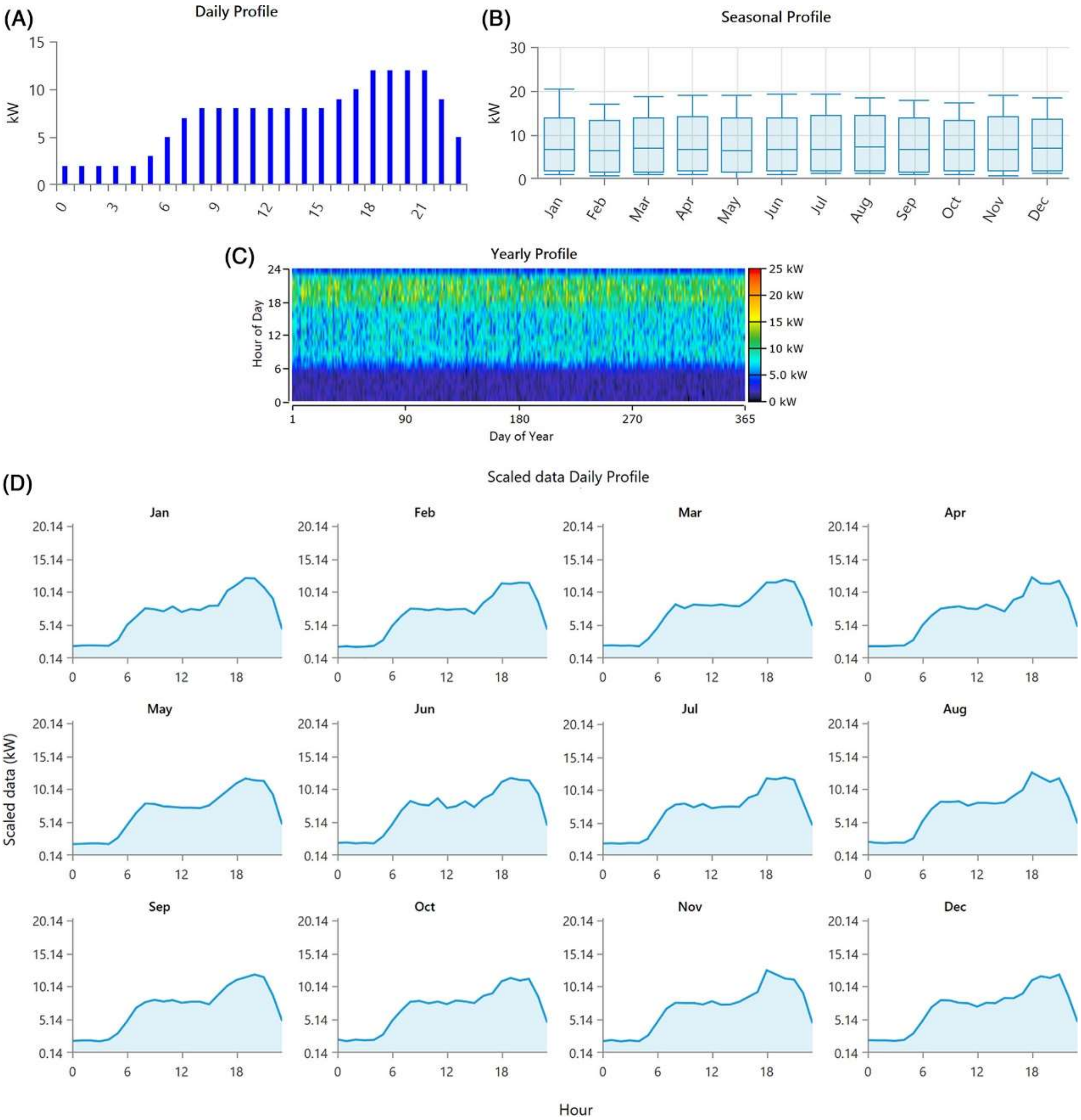

Fig. 9: (a) Daily load profile 1, (b) Montly load profile 1 and (c) Yearly load profile 1. (d) Daily load profile 1 from January to December.

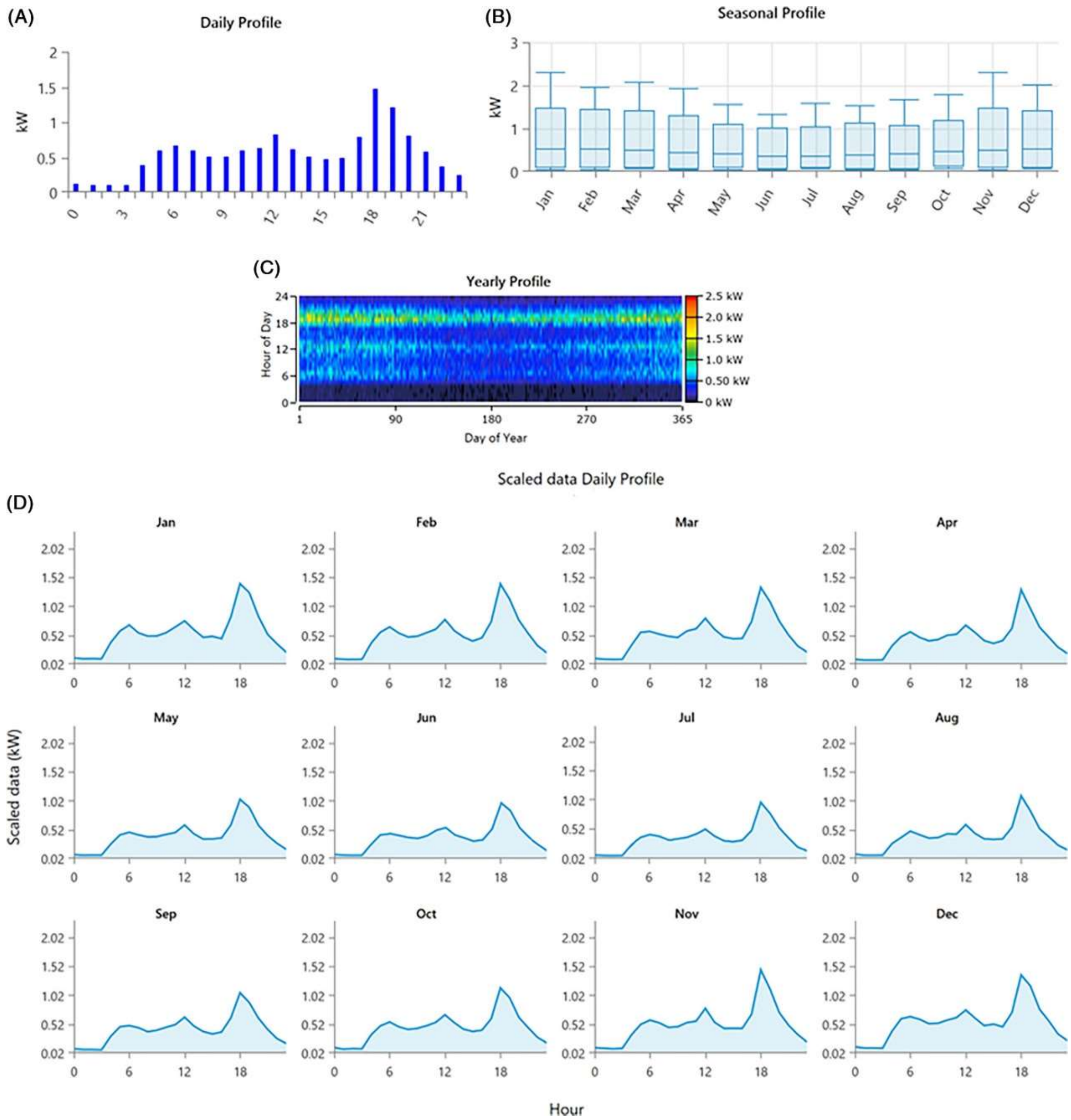

Fig. 10: (a) Daily load profile 2, (b) Montly load profile 2 and (c) Yearly load profile 2. (d) Daily load profile 2 from January to December.

7. RESULTS AND DISCUSSIONS

In the study, a generalized model has been developed to investigate the techno-economic effects of RERs in a microgrid system using the HOMER Pro software. The economic viability of the power system is determined when its configurations and capacities are sorted out having considered some significant parameters. In the study, four case studies as presented in Table 2 are assessed to determine the best optimized scenario, having used the meteorological data of the selected location based the National Aeronautics and Space Administration (NASA) database [35]. The configurations of the power system are technically and economically discussed as follows:

Table 2. Configurations of the proposed power system.

Case study	PV	DG	MG	BS
1	✓	✓	✓	✓
2	✓	✓	×	✓
3	✓	×	✓	✓
4	×	✓	×	×

7.1. Case study 1

The configuration presented in this case study consists of a mixed power sources such as PV, DG, MG and BS. The PV, DG and MG contribute respectively 66,395 kWh/yr (90.1%), 6,184 kWh/yr (9.24%) and 510 kWh/yr (0.692) of an annual electricity production of 73720 kWh/yr as presented in Fig. 11a. The monthly contribution of each component of the proposed power system is presented in Fig. 12a. It is obvious from the results presented in Fig. 12a that the power produced by the PV system is highly sufficient to meet the load demand in the months of January, Febuary, November and December. This is attributed to the availability of solar resources in the aforementioned months. Meanwhile, the excess electricity, unmet electric load and capacity shortage for this case study are 1,046 kWh/yr (1.42%), 0 kWh/yr (0%) and 0.445 kWh/yr (0.00070%). The optimized system resulted in the following economic indicators: NPC_{total} of $213,405.4, COE of $0.256/kWh, ACS of $16,508, annual worth of $21,013, an ROI of 18.7%, IRR of 22.8% and RF of 88.6% as presented in Table 3. This has resulted in NPC_{total}, COE and ACS savings of $216238, 0.259 $/kWh and $16729 when compared with case study 4. The cash flow summary and NPC of the system are presented in Fig. 13 and Table 4. Moreover, the DG runs for 1037 h/yr with the capacity factor (CF) of 3.89% and 3055.50 L of diesel fuel to generate 6814.363 kWh/yr of electricity. This has led to 88.35% and 80.10% reduction in the diesel fuel and operating hours of the DG when compared with the base case study. Meanwhile, the MG operates for 340 h/yr with the CF of 3.88% and 408 L of methanol fuel to produce electricity of 510 kWh/yr. The environmental indicators obtained in the study are Carbon dioxide (CO_2) of 8605 kg/yr, Carbon monoxide (CO) of 56 kg/yr, Unburned hydrocarbon (UCH) of 2.27 kg/yr, Particulate matter (PM) of 3.39 kg/yr, Sulphur dioxide (SO_2) of 21.7 kg/yr and Nitrogen dioxides (NO_x) of 63.7 kg/yr. This indicates that the above mentioned emissions have been reduced by 60038 kg/yr, 410 kg/yr, 16.63 kg/yr, 24.81 kg/yr, 146.3 kg/yr and 465.3 kg/yr. It is noted from the results obtained in this case study that it has the best environmental and economic performance when compared with other case studies. This has demonstrated that the presence of RERs enhances the techno-economic performance of a microgrid system and reduces operation of the DG.

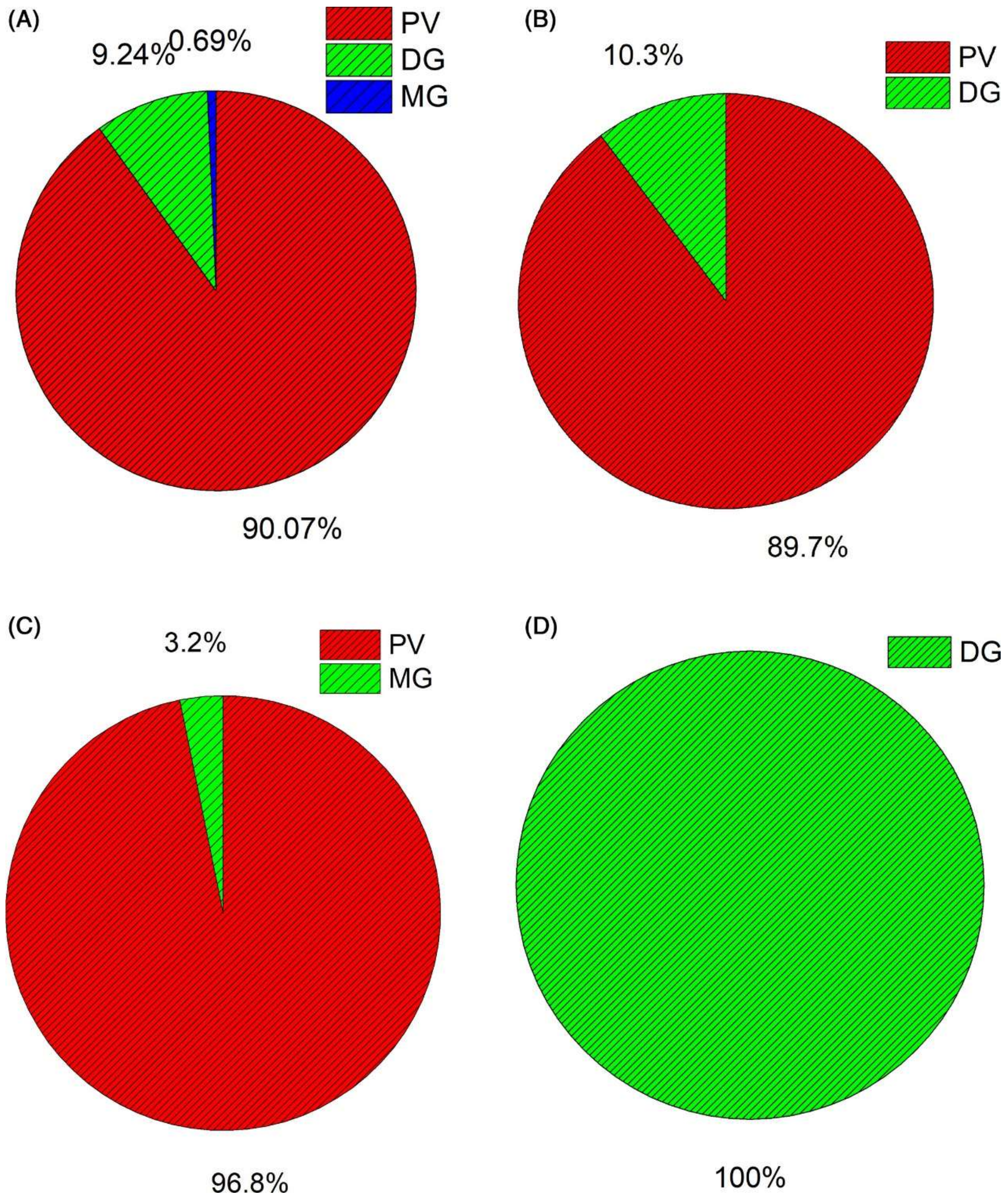

Fig. 11: Percentage of electric production from each component: (a) case study 1, (b) case study 2, (c) case study 3 and (d) case study 4.

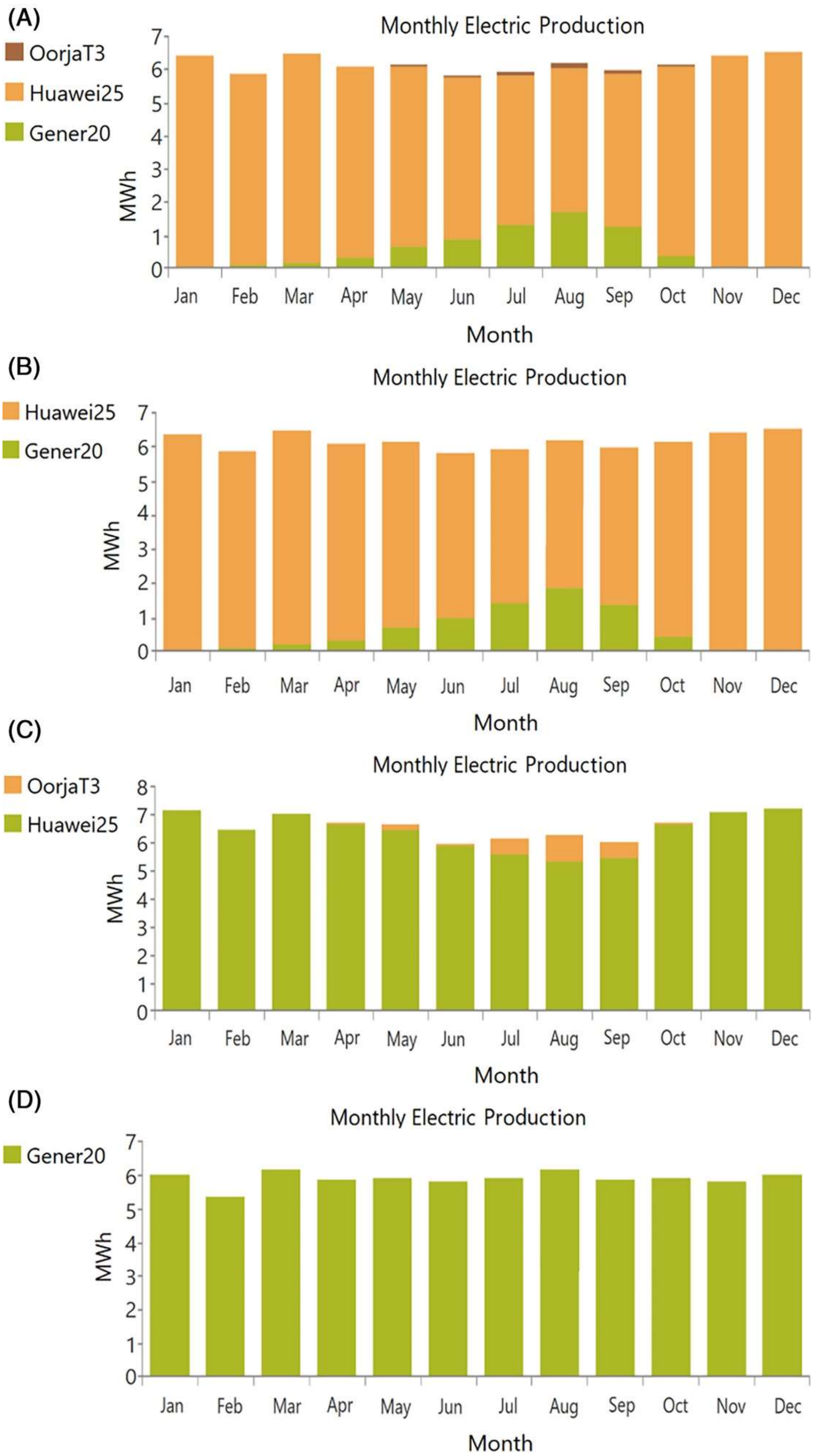

Fig. 12: Monthly electric production for (a) case study 1, (b) case study 2, (c) case study 3 and (d) case study 4.

Table 3: Optimised results obtained from the study.

Case study	Operating cost ($)	COE ($/kWh)	NPC ($)	ACS ($)	Annual worth ($/yr)	ROI (%)	IRR (%)
1	5490.95	0.256	213,405.4	16,508	21,013	18.7	22.8
2	5721.6	0.257	214,444.5	16,588	20,932	18.8	22.9
3	3294.991	0.299	248,930.9	19,256	18,265	12.7	16.4
4	32785.08	0.515	429,673.4	33,237	4,283	108.4	119.8

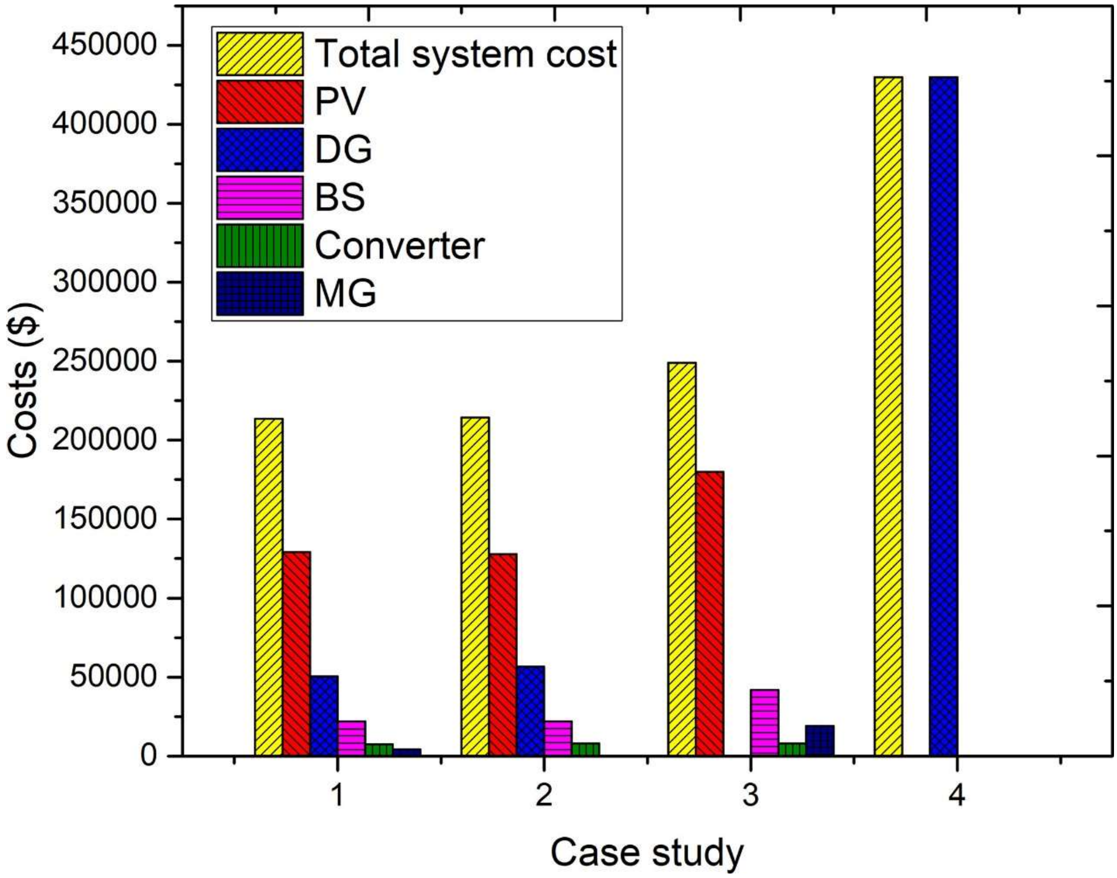

Fig. 13: Cash flow summary for the configurations.

Table 4: Net present costs of the system.

Case study	Capital ($)	Operating ($)	Replacement ($)	Salvage ($)	Resource ($)	Total NPC ($)
1	142,421	10,048	12,067	-1,695	50,565	213,405
2	140,478	10,014	12,393	-1,529	53,089	214,445
3	206,335	19,158	13,231	-5,495	15,702	248,931
4	6,081	2,797	14,361	-672.85	407,107	429,673

7.2. Case study 2

In this case study, PV, DG and BS are energy sources allocated to satisfy the load demand. The total electricity produced from this scenario is 73,608 kWh/yr, where the

PV and DG contribute 66,059 kWh/yr and 7,549 kWh/yr that are equivalent to 89.7% and 10.3% of the total energy generated as presented in Fig. 11b. While the monthly contribution of all the components of the proposed power system is presented in Fig. 12b. It is noticed that the power generated from the PV system in this case study maintain a similar trend in the months of January, Febuary, November and December when compared with case study 1. It can be seen from the results obtained that the excess energy production is 894 kWh/yr about 1.22% of the total energy generated, unmet electrical load of 0 kWh/yr (0%) and capacity shortage of 5.91 kWh/yr (0.00920%). The economic indicators obtained in this case study are as follows: NPC_{total} of $214,444.5 COE of $0.257/kWh, ACS of $16,588, annual worth of $20,932, an ROI of 18.8%, IRR of 22.9% and RF of 88.3% as presented in Table 3. This has resulted in NPC_{total}, COE and ACS savings of $215228.9, $0.043/kWh and $16729 when compared with case study 4. While Fig. 13 and Table 4 depict the cash flow summary and NPC of the power system. The DG operates in this case study for 1193 h/yr with the CF of 4.31% and 3422 L of diesel fuel to produce 7549 kWh/yr of electricity. This has resulted in 86.96% and 77.11% reduction in the diesel fuel and operating hours of the DG when compare with the base case study. Therefore, PV-DG-BS configuration is considered marginally cost-effective power solution when compared with using only the DG to meet the load demand. The emissions obtained in the study are CO_2 of 8951 kg/yr, CO of 60.7 kg/yr, UCH of 2.46 kg/yr, PM of 3.68 kg/yr, SO_2 of 21.9 kg/yr and NO_x of 69 kg/yr. The above mentioned emissions have been reduced by 59,692 kg/yr, 405.3 kg/yr, 16.44 kg/yr, 24.52 kg/yr, 146.1 kg/yr and 460 kg/yr when compared with case study 4. The limited operating hours of the DG have reduced the emission and operating cost of the power system. It can be deduced from the above mentioned discussion that case study 2 is technically and environmentally similar to case study 1. However, marginal higher NPC_{total}, COE, operating cost, ACS and emissions make the operation of case study 2 to be complicated and not attractive when compared to case study 1.

7.3. Case study 3

The configuration of a microgrid system proposed in this case study consists of PV, MG and BS for an islanding operation. The contribution of the PV is 76,651 kWh/yr (96.8%) and MG produces 2530 kWh (3.20%) of the total electricity supplied from the aforementioned generating units that is equal to 79,181 kWh/yr as presented in Fig. 11c. The monthly contribution of each component of the total electricity produced is presented in Fig. 12c where the share of power obtained from the PV system is more than the MG. Whereas, the excess energy production, unmet electrical load and capacity shortage are 5840 kWh/yr (7.38%), 19.9 kWh/yr (0.0309%) and 52.4 kWh/yr (0.0812%) of the total energy generation. The results obtained reveal that this configuration generates higher excess energy compared to case studies 1 and 2. This shows that the configuration is marginally economically feasible when compared with the base case study with NPC_{total} of $248930.9, COE of $0.299/kWh, ACS of $19256, annual worth of $18,265, an ROI of 12.7%, IRR of 16.4% and RF of 96.1 % as presented in Table 3. This has resulted in NPC_{total}, COE and ACS savings of \$215228.9, \$0.043/kWh and \$16729 when compared with case study 4. The NPC_{total} and COE obtained in this case study are slightly higher than the NPC_{total} and COE of the first case study. The cash flow summary and NPC of the system are presented in Fig. 13 and Table 4. The MG operates for 1687 h/yr with fuel consumption of 2,024 L/yr to generate 2530.3 kWh/yr of electricity at CF of 19.3%. It is noted that the running hours and methanol consumption of the MG in this case study have increased tremendously with the application of the PV, MG and BS when compared with the case study 1. It produces CO_2 of 3,042 kg/yr, CO of 8.98 kg/yr, UCH of 0.364 kg/yr, PM of 0.545 kg/yr, SO_2 of 10.5 and NO_x of 10.2 kg/yr. It is well noted from the results obtained from this configuration that it provides a reduction of CO_2, CO, UCH, PM, SO_2 and NOx of 65601 kg/yr, 410 kg/yr, 16.63 kg/yr, 24.81 kg/yr, 146. 3 kg/yr and 465.3 kg/yr when compared with the base case study. The amount of pollution reduction obtained in this case study is related to the RF of the system.

7.4. Case study 4

The size of the DG considered is 20 kW where the energy generated is 68,289 kWh/yr as presented in Fig. 11d and the monthly electricity generation of the DG is presented in Fig. 12d. The excess electricity is 0 kWh, the unmet electric load is 0 kWh/yr and capacity shortage is 0 kWh/yr. From the above discussion, it indicates that the load demand is 100% depended on the DG that is characterized by highly intensive emission and a very expensive operation owing to high costs of fossil fuel, maintenance and logistics. The results obtained from this case study demonstrate that the system has the NPC_{total} of \$429,673.4, COE of \$0.515/kWh, ACS of \$33,237,annual worth of \$4,283, an ROI of 108.4 %, IRR of 119.8% and FR of 0 % as presented in Table 3. It can be seen that the utilization of the DG only has the highest NPC_{total}, ACS and COE when compared with the other case studies. The cash flow summary and NPC of the system are presented in Fig. 13 and Table 4. The high cost of diesel fuel coupled with the complex nature of the DG with a large number of share makes its operation to require frequent maintenance, this makes the system infeasible for an islanding operation. For this reason, it is not economically viable to use the DG only for an islanding system in the presence of RERs. Therefore, green energy based microgrid system is considered as a cost-effective solution in comparison to the DG alone. It is worthwhile noting that the DG operated for 5212 hours to generate electricity of 68, 289 kWh/yr at CF of 39% with 26,242.8 L of diesel fuel at \$31085.58/yr. The DG produces CO_2 of 68,643 kg/yr, CO of 466 kg/yr, UCH of 18.9 kg/yr, PM of 28.2 kg/yr, SO_2 of 168 and NO_x of 529 kg/yr when it is used only to meet the load demand. It can be deduced from the results obtained in this scenario that it provides more emissions when compared with other case studies. This shows that increase in the operating hours of the DG causes a substantial increase in the fuel consumption and emissions.

7.5. Comparison of techno-economic aspects

The outcome of the study indicates that the PV-DG-MG-BS configuration is the optimum architecture with the least COE of 0.256 \$/kWh and minimum total NPC of

$213,405.4 at 0% unmet electric load. The renewable energy strategy as can be found in case study 1 offers the best results when compared with other case studies. It can be seen that savings of 50.29% in COE and 50.33% in NPC_{total} are obtained with a PV-DG-MG-BS strategy compared to a configuration that operates with the DG only. The values of COE and NPC_{total} have reduced considerably owing to decrease in the operating cost. The 83.25 % reduction in the operating cost was caused by a 90.9% reduction in the electricity produced by the DG when compared with the case study 4. The utilization of RERs in this case study resulted in 59% diesel fuel saving when compared with case study 4. It can be seen from the case studies that the utilization of RERs is the best option to solve the global energy crisis. This will reduce the burden on the depleted fossil fuels and reduce the COE to a reasonable level that can be accepted by consumers.

8. SENSITIVITY ANALYSIS

The sensitivity analysis is presented in the study to evaluate the performance of the power system under different uncertain parameters. The impacts of these sensitivity variables on the techno-economic performance of the proposed microgrid system were taken into consideration in the study. This allows the MGOs to predict the characteristics of their power systems when operating with a number of conditions.

8.1. Impacts of variation of diesel price

The global variation in the price of diesel is sensitive to the performance of the power system. This demonstrates that fluctuation in the price of diesel is one of the significant factors for economic analysis of the power system. In this study, the diesel fuel price was varied from 0.6 $/L to 1.4 $/L and its impacts on the NPC_{total} and COE were evaluated as presented in Fig. 14. The result shows that the NPC_{total} increases from $186491 to $221226 as the price of diesel fuel increases. The COE also increases from 0.224 $/kWh to 0.265 $/kWh with an increase in the price of diesel. It can be deduced from the above discussion that the sensitivity analysis provides a clear idea about diesel price and its associated relationship with the COE and NPC_{total}.

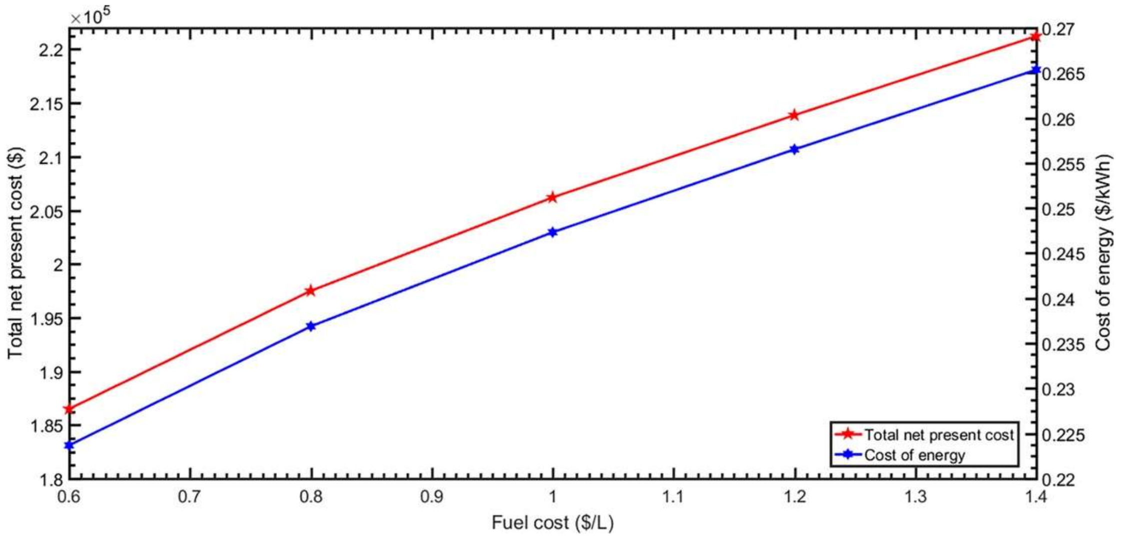

Fig. 14: Effect of diesel fuel cost variation on NPC_{total} and COE.

8.2. Impacts of variation of methanol price

The price of methanol has been varied from $ 0.2/L to $ 1.0/L to obtain the estimated value of COE and NPC_{total}. The COE and NPC_{total} of an integrated power system have changed from $ 0.254/kWh to $0.259/kWh and $ 212043.3 to $215905.9 when methanol price varied from $ 0.2/L to $ 1.0/L as shown in Fig.15. The results obtained from the sensitivity analysis indicate that the NPC_{total} and COE increase with an increase in price of methanol.

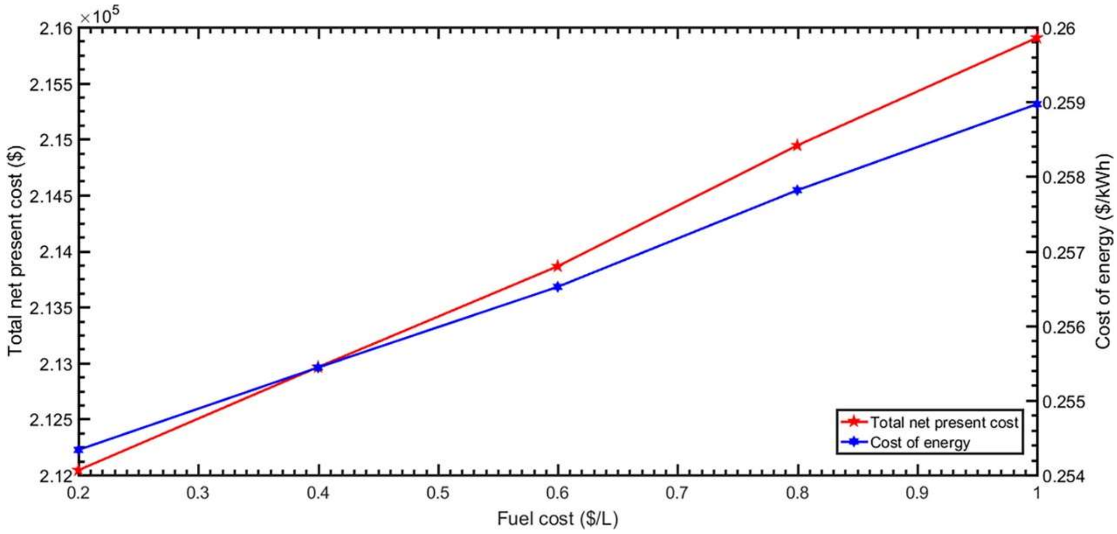

Fig. 15: Effect of methanol fuel cost variation on NPC_{total} and COE.

8.3. Impacts of variation of inflation rate

The effects of varying the inflation rate on the operation of the power system are investigated in this section by using the COE and NPC_{total}. The NPC_{total} increases from $204222.9 to $485133.4 with an increasing inflation rate from 0.5% to 2%. Similarly, the COE decreases from $ 0.282/kWh to $0.582/ kWh as the inflation rate increases from 0.5% to 2%. The results presented in Fig. 16 demonstrate that the variation in the inflation rate has a considerable effect on the above-mentioned KPIs. This shows that the inflation rate at the design stage of a renewable energy project affects the costs of procurements and installation of the essential components of the project.

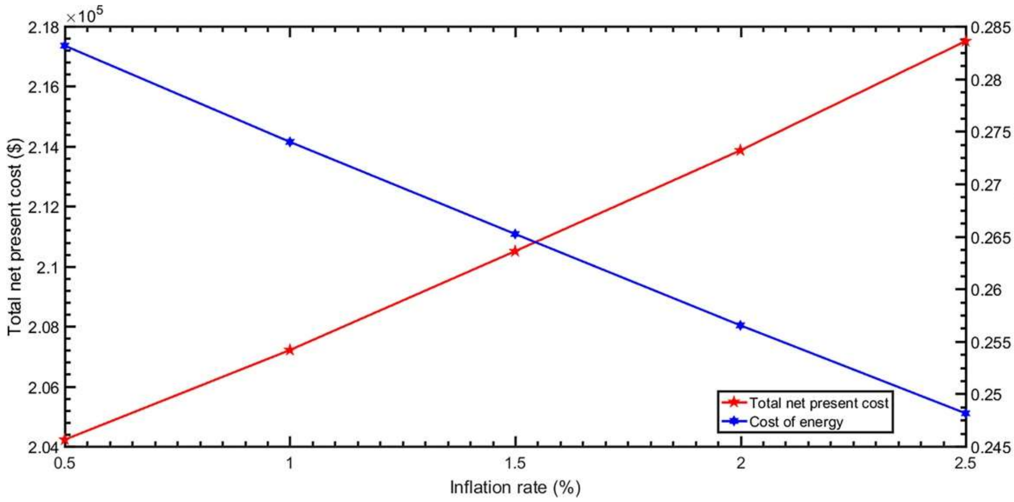

Fig. 16: Effect of inflation rate variation on NPC_{total} and COE.

8.4. Variation of the solar radiation

The solar radiation was varied from 2 kWh/m^2 to 10 kWh/m^2 and its impacts on the NPC_{total} and COE were analyzed. It can be observed from Fig. 17 that with an increase in solar radiation, the NPC_{total} diminishes from \$4000000 to \$200000.0843 and COE decreases from \$0.45/kWh to \$0.22/kWh. The solar radiation has an inverse impact on the NPC_{total} and COE, this shows that the higher the value of solar radiation, the lower the values of NPC_{total} and COE.

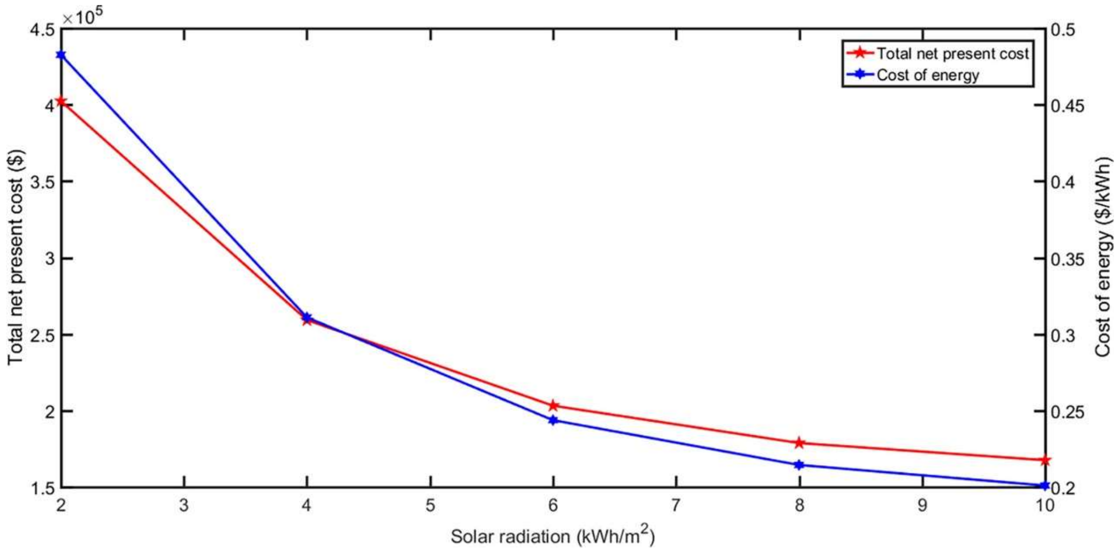

Fig. 17: Effect of solar radiation variation on NPC_{total} and COE.

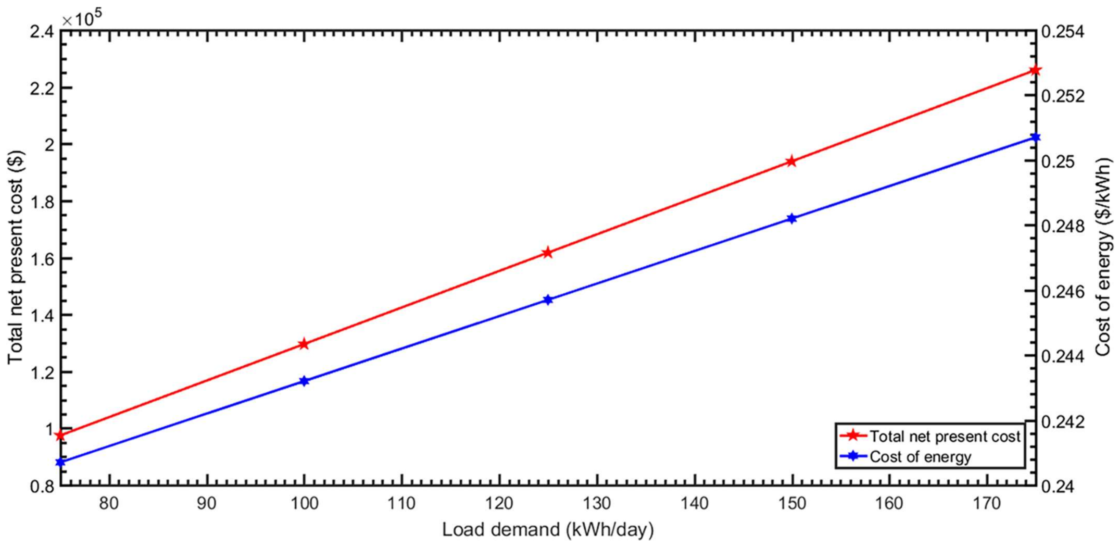

Fig. 18: Effect of load demand on NPC_{total} and COE.

8.5. Variation of the load demand

The effects of load demand are investigated in this section by varying the load demand from 75 kWh/day to 175 kW/day. It is obvious that there is a significant increase in the value COE from \$0.2407 kWh to \$0.2507/kWh. The NPC_{total} increases from \$97480.8 to \$225980.8 with an increase in the load demand as shown in Fig. 18. This shows that increase in the load growth has a substantial effect on the operation of the power system.

The results obtained in this section indicate that the load growth is one of the significant factors that can be used by the utilities to assess the performance of their power systems, since the utilization of new electrical appliances is expected to increase the load demand.

9. CONCLUSION

This paper presented a techno-economic analysis of an islanding PV-DG-MG-BS microgrid system that is structured to satisfy the power demand of the selected study area. The research work investigates the impacts of RERs on the technical and economic performance of the power system. The application of RERs in the research work reduces the operating hours, minimizes fuel consumption and emissions of the DG as well as ensuring a substantial improvement in financial feasibility of the power system. The results obtained from the simulation reveal that the utilization of the proposed microgrid system can considerably reduce over dependence on fossil fuels. This indicates that a PV-DG-MG-BS microgrid system is economically feasible owing to persistent global fluctuation of diesel fuel price. It is also established from the study that the proposed power system achieved a substantial reduction in the COE and NPC_{total} when compared to a circumstance where the DG is only used. The most optimized configuration provides electricity at the rate of 0.256 $/kWh and NPC_{total} of $213,405.4, this is 50.29% and 50.33% lower than the base case study. This shows that the proposed power system is cost-effective and environmentally friendly to provide a clean energy solution and improves access to electricity. The power system presented can provide job opportunities, improve the standard of living and increase the well-being and economic activities of the rural dwellers where the proposed microgrid system is sited. Finally, the research output can be utilized by many international organizations as the benchmarks for the design and development of sustainable energy to ensure a secured and reliable power supply.

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