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Reliability, economic and environmental analysis of a microgrid system in the presence of renewable energy resources

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HIGHLIGHTS

- The cost-effectiveness of using green technologies is proposed in this work.
- The technique reduces the cost of energy, lifecycle cost and lifecycle emission.
- The proposed method can be used for economic planning of renewable energy project.
- RERs can reduce the number of people without access to electricity.
- The improved overall benefit that is achieved in this research work.

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ABSTRACT

The application of renewable energy resources in a power system has received significant attention owing to the environmental impacts and fluctuations of fossil fuel prices. Consequently, renewable energy resources have become important sources to generate power at the commercial level due to their various benefits, coupled with the government incentives and public supports. This research work is focused on the evaluation of the reliability, economic and environmental benefits of renewable energy resources in a microgrid system. The lifecycle analysis of a microgrid system that consists of the photovoltaic, wind turbine generator, electric storage system and diesel generator is implemented in this study to test their commercial prospects in rural communities that have no access to electricity due to economic and technical constraints. The objective of this research work is to minimize the cost of energy, lifecycle cost, the annual cost of load loss and lifecycle greenhouse gas emission cost as well as to improve the overall benefit of green technologies in the proposed microgrid system. This objective is achieved by utilizing the basic probability concept to obtain the reliability performance indicators such as expected energy not served, loss of load expectation and loss of load probability, in addition to utilizing an fmincon optimization tool in the MATLAB environment to investigate the environmental and economic effects of renewable energy resources in a power system. The suitability of the model is tested on six case studies by using the same load profile, wind speed and irradiation of the site and diesel generator power capacity. The market factors such as interest rate and price of diesel fuel as well as forced outage rate, annual peak load variation and distributed generation penetration level are utilized to study their impacts on the operation of a microgrid system. The results obtained in this study demonstrate the optimal feasibility of renewable energy resources in a microgrid system. This indicates that it offers a significant reduction in the values of lifecycle cost, cost of energy, greenhouse gas emission cost and the annual cost of load loss when compared with case study 1. This research work shows that the utilization of green technologies in a microgrid system optimizes the reliability, cost savings, lifecycle cost and environmental impact. The technique adopted in the study can serve as a reference for rural electrification projects and solve socioeconomic problems that are associated with power outages.

1. Introduction

The socio-economic development and gross domestic product (GDP) of any nation depend on the effectiveness of its power systems and the availability of power supply at the load centres. However, many countries are currently facing several challenges in their power sectors

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owing to fuel constraints, dilapidating infrastructure, inappropriate investment policies, high transmission and distribution system losses, capital constraint, poor operating performance, manpower issues, institutional and management issues, environmental implications of conventional generating units, etc. The aforementioned factors have caused a substantial deficit between the power demand and power supply in the developing nations [1]. Moreover, the failure of several countries to make up for the current power shortage has caused a poor standard of living for their citizens and the energy crisis that impedes many rural electrification projects [2]. Presently, the number of people without access to electrical energy has been estimated to be about 1.1 billion [3]. This shows that 17% of the world population has no access to electric power supply. About 22% of the general population that have no access to electrical energy are living in remote communities of undeveloped and developing nations despite efforts made by different organizations to bring power supplies to those areas. At the same time, in rural areas, grid connection is difficult owing to some technical limitations such as geographical terrain and remoteness of various rural areas from the grid [4]. Apart from this, the economics of scale does not support the huge investment required for grid extension to rural areas on the basis of a small population. In view of this, alternative sources of power are proposed by the utilities to take care of the power demand by the general population of the people that are living in such locations [5]. The deployment of renewable energy resources (RERs) into the utility grid as a measure to reduce the amount of the annual greenhouse gas (GHG) emissions, enhance energy efficiency, improve power system reliability and reduce operation and maintenance (O&M) costs has been the priority of many countries for sustainable energy development [6]. The access to a reliable power supply has become a global phenomenon based on population growth, socio-economic development and environmental sustainability. The application of RERs based on sustainable energy development goals that have been initiated in some countries has significantly increased the number of people that have access to electricity. The improvements in the technologies and decline in the costs of renewable energy components have provided alternative power solutions for those without access to electricity. This has reduced the number of people without access to electricity to 1.1 billion people, the first time that such a positive trend will be observed in the history of human civilization [3].

The sudden increase in the price of fossil fuel has made green technologies highly competitive with brown technologies and create a favourable condition for their integration into the microgrid systems. This indicates that RERs have become a potential alternative to solve the power outage problem in remote areas of some countries where access to a reliable power supply is limited owing to some financial and technical barriers. The sources including, the diesel generator, microturbine, photovoltaic (PV), wind turbine generator (WTG), electric storage system (ESS), mini-hydro and micro-hydro, fuel cells fired by natural gas or biomass and biomass combustion are utilized to meet load demands irrespective of the location and time. The technical, environmental and economic benefits of green technologies have increased their applications in the grid-connected and off-grid power systems due to the fact that they will not incur fuel costs unlike brown technologies [7]. However, the seasonal intermittency of wind speed and solar resources and dependency of the WTG and PV on climate and weather conditions have created a serious challenge for the utilities. Owing to this, PV and WTG will only be able to meet the power specifications of the consumers subject to the availability of adequate wind and solar resources [8]. Therefore, the economic feasibility to increase the number of the WTG and PV in the microgrid systems due to the intermittent nature of local renewable energy sources has caused a serious business risk [9]. Under such circumstances, a battery system is required to back up the microgrid system in a situation where solar irradiation and wind speed are not adequately available, i.e. wind speed is below the cut-in speed and solar irradiation is not adequate to make the PV panel operational. Consequently, the diesel generators are widely utilized in remote areas that have no access to electrical energy because they are independent of climatic change and predictable [9].

However, the application of the diesel generator has the following setbacks, i.e. more expensive, not environmentally friendly due the GHG emissions, fluctuating price of fuel can affect its operation, non-availability of fuel can cause a widespread power outage, noise pollution, high O&M costs, time-consuming when setting up the generator in comparison to others, not cost effective when compared with the PV and WTG, etc. A few initiatives have been launched to combine the operation of green technologies and brown technologies in the microgrid systems, but their shortcomings have hindered their utilization in the power system. In view of this, the strength of RERs can be effectively utilized to complement the weakness of conventional generating units and vice-versa. This indicates that different sources of energy are meant to complement one another to some degree. Moreover, the microgrid system that has multiple power sources is much better than the microgrid system that utilizes a single power source in relations to the reliability, technical, environmental and economic benefits. The PV and WTG have been reported to be the most popular renewable distributed energy resources based on the availability, affordability, protection of the environment, cheaper than other low-emission technologies, clean energy options and more reliable price projections. The intermittent characteristics of solar irradiation and wind speed have prompted the integration of the ESS into a microgrid system as a measure to smooth out the effects of fluctuating weather conditions [10].

The assessment of a microgrid system has been carried out by utilizing various performance models and indicators, optimization software tools and methods. This indicates that several research works have reported the significance of the microgrid system in rural communities. Li et al. [11,6] have proposed a hazard constrained stochastic monetary dispatch considering the reliance among wind speeds of different wind farms with pair-copula. Roy et al. [2] have performed a lifecycle analysis for a standalone power system by using the PV, diesel and petrol generators. The authors have tested the prospects of the aforementioned generating units in the remote regions of Bangladesh that have no access to a power supply from the national grid. Malheiro et al. [12] have proposed a mixed-integer linear programming for sizing and scheduling of wind/PV/diesel/battery standalone system for a one-year time horizon. The objective of the study is accomplished with regard to the optimization of the levelized cost of energy (LCOE) over a lifetime of 20 years by taking into the consideration the hourly changes in the solar and wind resources and power demand. Das et al. [13] have implemented comparative analyses of a standalone power system that consists of PV, battery, micro gas turbines and internal combustion engines. The research work is focused on the optimization of the cost of energy (COE), waste heat and lifetime Carbon dioxide (CO_2) emissions with the application of a genetic algorithm (GA). Moreover, Dufo-López et al. [14] have utilized the Pareto evolutionary algorithm in a PV/wind/battery/diesel standalone power system. The multi-objective optimization technique is proposed in the study to minimize the LCOE and lifecycle (LCC) emissions of CO_2. Similarly, Singh et al. [15] have proposed Artificial Bee Colony to optimize the net present cost (NPC), LCOE and annualized cost of a standalone system that comprises WTG, biomass, PV and ESS in Patiala, a small community in Punjab, India.

In another work, Ma et al. [16] have proposed a feasibility study and techno-economic evaluation of a solar/wind/battery hybrid system for a remote Island in Hong Kong, China. The authors have utilized the HOMER software to perform the techno-economic evaluation of the proposed hybrid system on the basis of minimizing the NPC and COE. Furthermore, Zhao et al. [17] have presented a GA for assessment of the WTG/PV/diesel generator/battery storage microgrid system in Dongfushan Island, Zhejiang Province, China. The algorithm is used for the minimization of the LCC and greenhouse gas (GHG) emission cost (GEC_{total}) as well as the maximization of RERs penetration level in a standalone power system. Brodrick et al. [18] have presented bi-objective Pareto fronts to optimize the trade-off between integrated solar

Table 1
A literature review of various work on hybrid/microgrid/smart grid power system.

Architecture	Technical parameters											
	Components										Method utilized	Objective functions
	EWH	PV	WTG	DG	ESS	HYD	FC	MT	BM	EV		
Hybrid system [22]	✗	✓	✗	✓	✓	✗	✗	✗	✗	✗	HOMER	COE
MG system [23]	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	CPLEX solver	Costs
Hybrid system [24]	✗	✓	✗	✗	✓	✗	✗	✗	✓	✗	HOMER	COE and NPC
An off grid house [25]	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	GA-PSO and MOPSO	LPSP, TPC and COE
Domestic, industrial, agricultural, BTS load [26]	✗	✓	✓	✗	✓	✓	✗	✗	✗	✗	HOMER	NPC, COE and CO_2
A grid-connected HRES [27]	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	GA	LC and CEP
A smart MG [28]	✗	✓	✓	✓	✓	✗	✓	✓	✗	✗	MOPSO	OCs and Emissions
A smart household system [29]	✓	✓	✗	✗	✓	✗	✗	✗	✗	✓	HEMS	COE
Smart grid technology [30]	✗	✓	✗	✗	✓	✗	✗	✗	✗	✓	DRSM	EC and PL
Standalone MG system [17]	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	GA	Emissions, LCC and MRP
A grid connected system [31]	✗	✓	✓	✗	✓	✗	✓	✓	✗	✗	NET	Cost
A grid connected MG system [32]	✗	✓	✗	✗	✓	✗	✓	✗	✗	✗	GA	NTW
Hybrid energy system [33]	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	PSO, TS, SA, IHSBSA and ABSO	LPSP and TAC
Standalone system [34]	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	MOEA	NPC HDI and JC
Standalone HRES [35]	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	MOP	LCC, EE and LPSP
Standalone HRES [36]	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	PICEA	ACS, LSPS and FE
Hybrid energy system [37]	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	CS	TSC
HRES [38]	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	CS	Cost and CO_2 emission
Roof top wind turbines [39]	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	EPR	TP and LLV
HRES [40]	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	CCP	TSC and reliability
Distribution networks [41]	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	ABCA	VPI, LLM and PLR
HEMS [42]	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	MILP	CPG
A grid connected MG system [43]	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	Typical	LCOES and LVOES
Distribution system [44]	✗	✓	✓	✗	✗	✗	✗	✓	✗	✗	MOALO	IB, SVS and LL
CES [45]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	Typical	LCOES and IRR
RTS [46]	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	CPLEX	CEP
CES [47]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	GA	ELR, CER and VS
IEEE test system [48]	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	MILP	OTC

Key: ABCA = Artificial bee colony algorithm, optimization, ABSO = Artificial bee swarm optimization, ACS = Annualized cost of system, BTS = Base transceiver station, CEP = Cost of electricity purchase, CER = CO_2 emission reduction, CES = Community energy storage, CPG = Costs of power from the grid, CS = Cuckoo Search, CCP = Chance constrained programming, DRSM = demand response scheduling model, EC = electricity consumption, EE = Embodied energy, ELR = Energy loss reduction, EPR = Evolutionary polynomial regression, EWH = Electric water heater, EV = Electric vehicle, FE = Fuel emissions, GA = Genetic algorithm, GA-PSO = Genetic algorithm particle swarm optimization, HDI = Human development index, HEMS = Home energy management system, HRES = Hybrid renewable energy system, IB = Investment benefits, IHSBSA = Improved harmony search-based simulated annealing, IPSO = Improved particle swarm optimization, IRR = internal rate of return, JC = Job creation, LCC = lifecycle cost, LCOES = Levelised cost of energy storage, LL = Line losses, LLM = line loading minimization, LLV = Land lease value, LPSP = Loss of power supply probability, LVOES = Levelised values of energy storage, MOALO = Multi-objective ant lion optimizer, MOEA = Multi-objective evolutionary algorithm, MRP = maximization of renewable energy source penetration, MILP = Mixed Integer Linear Programming, MOP = Multi-objective optimization, MOPSO = Multi-objective particle swarm optimization, NET = New evolutionary technique, NTW = net present worth, OCs = operational costs, OTC = Overall total cost, PICEA = preference-inspired co-evolutionary algorithm, PL = peak load, PLR = Power loss reduction, PSO = Particle swarm optimization, RTS = Reliability test system, SA = Simulated annealing, SVS = System voltage stability, TS = Tabu search, TP = Total profit, TSC = Total system cost, TPC = Total present cost, VS = VAr support and VPI = voltage profile improvement.

combined cycle system economics and CO_2 emissions. The authors have carried out the sensitivity analysis of a power system based on the market mechanism such as discount rate and COE. Moreover, Ogunrinde et al. [19] have utilized a GA in the standalone hybrid system that comprises WTG, split diesel generator, PV and battery to minimize the dump energy, LCC and CO_2 of a residential building in Nigeria. While, Bortolini et al. [20] have presented a technique to optimize the carbon footprint and LCEO with the application of PV, battery and diesel generator hybrid system. Meanwhile, Chade et al. [21] have carried out the feasibility analysis of hydrogen and wind power system for Arctic isolated location in Grimsey Island, 40 km from the North Coast of Iceland. The simulation results indicate that a microgrid system is appropriate for the location, based on the minimal COE, NPC, simple payback period and internal rate return. In summary, the literature review of other work apart from the ones explained above are presented in Table 1.

As a measure to utilize RERs in a microgrid system efficiently and economically, the objective functions of the microgrid system should be updated with GHG emission, reliability indices, expected energy not served (EENS), loss of load expectation (LOLE), loss of load probability (LOLP), interruption cost, etc. Some of these objective functions can be accomplished with the application of a number of optimization methods. In addition to this, most of the works reviewed in this paper are focused on the objective functions that are primarily dominated by costs owing to the combination of RERs that give the optimal solutions. The objective functions that aforementioned researchers considered are combinations of LCOE, CO_2 emission, waste energy and NPC. None of these studies have applied the annual cost of load loss, reliability indices, GHG emissions, LCC and overall benefits ($O_{benefit}$) as the objective functions concurrently. Furthermore, most of the aforementioned studies do not consider the possibility of using multiple sources to reduce the costs that are related to the annual load loss and their impacts on the reduction of COE, LCC and GHG emissions. To the best of the authors' knowledge, no research work has performed a consolidated plan and operations optimization as presented in this paper. Such a comprehensive technique is necessary to analyze the economic, reliability and environmental benefits of RERs in a microgrid system.

This paper presents an fmincon in the MATLAB environment to achieve the objective of the work due to the following advantages: an fmincon has the capability to resolve large-scale programming problems as quickly as possible with a complete limitation support, it is a state of the art of optimization technique that can handle nonlinear and linear optimization problems, it is highly efficient and flexible, it can efficiently produce an optimal solution, it has the capability of supplying Hessian data and interior-point algorithm to enhance the heartiness of the solver. Similarly, it is easy to obtain the best possible solution with the application of the solver. The objective of this research work is to minimize the LCC, GHG emissions cost, COE and annual cost of load loss (AC_{loss}^{load}) with the application of multiple sources, at the same time to maximize the aggregate benefits of utilizing green technologies in the proposed microgrid system. The results obtained from the study show a significant reduction in the LCC, GHG emissions cost, COE and annual cost of loss load when compared with a situation where only the diesel generator is utilized to meet the power demand. The simulation results obtained in this study demonstrate the effectiveness of proposed multi-objective functions to solve numerous problems when compared with traditional single objective technique. The contribution of this study is to evaluate the effectiveness and capability of the PV/WTG/ESS/diesel generator microgrid system to meet the power requirements of consumers based on the availability of local wind and solar resources. The main contributions of this paper are summarized as follows:

- The multi-objective function is proposed in this research work to evaluate the comprehensive effects of the PV, WTG and ESS in a microgrid system.
- The reliability, economic and environmental benefits are considered in this research work with the objective of minimizing the LCC, COE and GHG emissions cost and maximizing the overall benefit.
- Mathematical modelling of the major components of the proposed microgrid system is presented.
- The forced outage rate, peak load variation and RERs and ESS penetration are studied on the reliability performance of a microgrid system.
- The market factors such as fuel price fluctuation, capital cost and interest rates are applied to analyze their effects on the economic performance of the proposed microgrid system.
- Assessment of the different operating strategies and cost analysis of a microgrid system are performed.
- Development and application of economic, environmental and reliability cost models for a microgrid system.

The remaining part of the paper is arranged as follows: The modelling of various components of the proposed microgrid system is presented in Section 2. The problem formulation coupled with the optimization problem is given in Section 3, followed by the cost assessment of the proposed microgrid system that is presented in Section 4. Section 5 focuses on the reliability evaluation of a microgrid system, while Section 6 presents the technical specifications, cost parameters and reliability indices for the case study analysis. The simulation results and discussions are presented in Section 7 while the sensitivity analysis of the proposed power system is performed in Section 8. Finally, Section 9 draws the conclusion of the research work.

2. Modelling of the proposed microgrid system

A microgrid is a small-scale power system or localized power station that has its own generation and storage resources and can operate independently or in parallel with other small power grids [4]. The operation of a microgrid system is typically supported by communication facility and distributed generation technologies such as PV, WTG, diesel generator and battery system as shown in Fig. 1. The main purpose of utilizing a microgrid system over a traditional power system in the rural communities that have no access to electricity due to economic and technical constraints is to defer the costs that are associated with construction of the new transmission and distribution lines, improve local energy delivery, improve the energy efficiency, achieve cost savings, improve grid safety by reducing the grid congestion, generate revenue for the utilities, make the grid more resilient, increase savings on energy bills, improve economic growth of the rural areas, reduce cost of electricity and ensure a reliable power supply as well as guarantee affordable energy security for the consumers, which will invariably lower the GHG emissions [49,50]. This research work is focused on the formulation of a model to evaluate the reliability, environmental and economic impacts of RERs and ESS in a microgrid system that serves off-grid location. The proposed power system is suitable for the remote communities where energy crisis has become a serious problem. The mathematical models of the major components of the proposed microgrid are briefly discussed as follows.

2.1. Modelling of diesel generator

The diesel generator is one of the components of a microgrid system that is designed for emergency standby power, limited time running power, prime running power and continuous operation power [51]. It is designed by the manufacturer so that it can quickly respond to load fluctuations based on its up and down ramping capability [52]. The diesel generator utilized in this research work can operate at 30–90% of its nominal rating specified by the manufacturer. In this subsection, the fuel cost that carries the largest percentage of the operating cost of the diesel generator is modelled. Hence, it can be estimated by using a quadratic polynomial as represented in Eq. (1) [4]:

$$FC = \sum_{i=1}^{n} (a + bP_i + cP_i^2)\ (\$/\text{hr}) \tag{1}$$

where n is the number of diesel generator and a, b and c are the cost coefficients of the diesel generator.

2.2. Modelling of electric storage system

The electric storage system is an electrochemical device that stores energy from various sources such as PV and WTG and it can be utilized for a number of applications. The ESS is mandatory in a microgrid system owing to the inherently stochastic characteristics of solar and wind resources. This requires the stored energy to be supplied to the load points in a situation where there is a shortage of energy. Similarly, it is designed to store the surplus power from the microgrid system whenever the power produced exceeds the power demanded by the consumers. The behaviour of the ESS can be assessed with the evaluation of the state of charge (SOC). The SOC of the ESS that is a function of time can be expressed in Eq. (2) as [4]:

$$SOC(t) = SOC(0) + \eta_c \sum_{m=1}^{N_{ess}} P_{ess}^{ch}(m, t) - \eta_d \sum_{n=1}^{N_{ess}} P_{ess}^{dis}(n, t) \tag{2}$$

where η_d and η_c are the discharging and charging efficiencies of the ESS, $P_{ess}^{ch}(m, t)$ is the power accepted by the ESS for charging application at time t and $P_{ess}^{dis}(n, t)$ is the power discharged from the ESS at time t.

The operation of the ESS depends on the charge and discharge limits, depth of discharge (DOD) and availability of the local wind and solar resources [5]. This indicates that the ESS must operate within allowable SOC limits specified by each manufacturer as presented in Eq. (3) as:

$$SOC^{\min}(t) \leqslant SOC(t) \leqslant SOC^{\max}(t) \tag{3}$$

The optimal operation of the ESS by considering the DOD can be expressed as:

$$SOC^{\min}(t) = (1 - DOD) \times SOC^{\max}(t) \tag{4}$$

2.3. Modelling of wind turbine system

The power curve can be utilized to measure the value of the power produced by the WTG as a function of wind speeds [53]. In view of this, the characteristic of the typical WTG that is utilized in this research

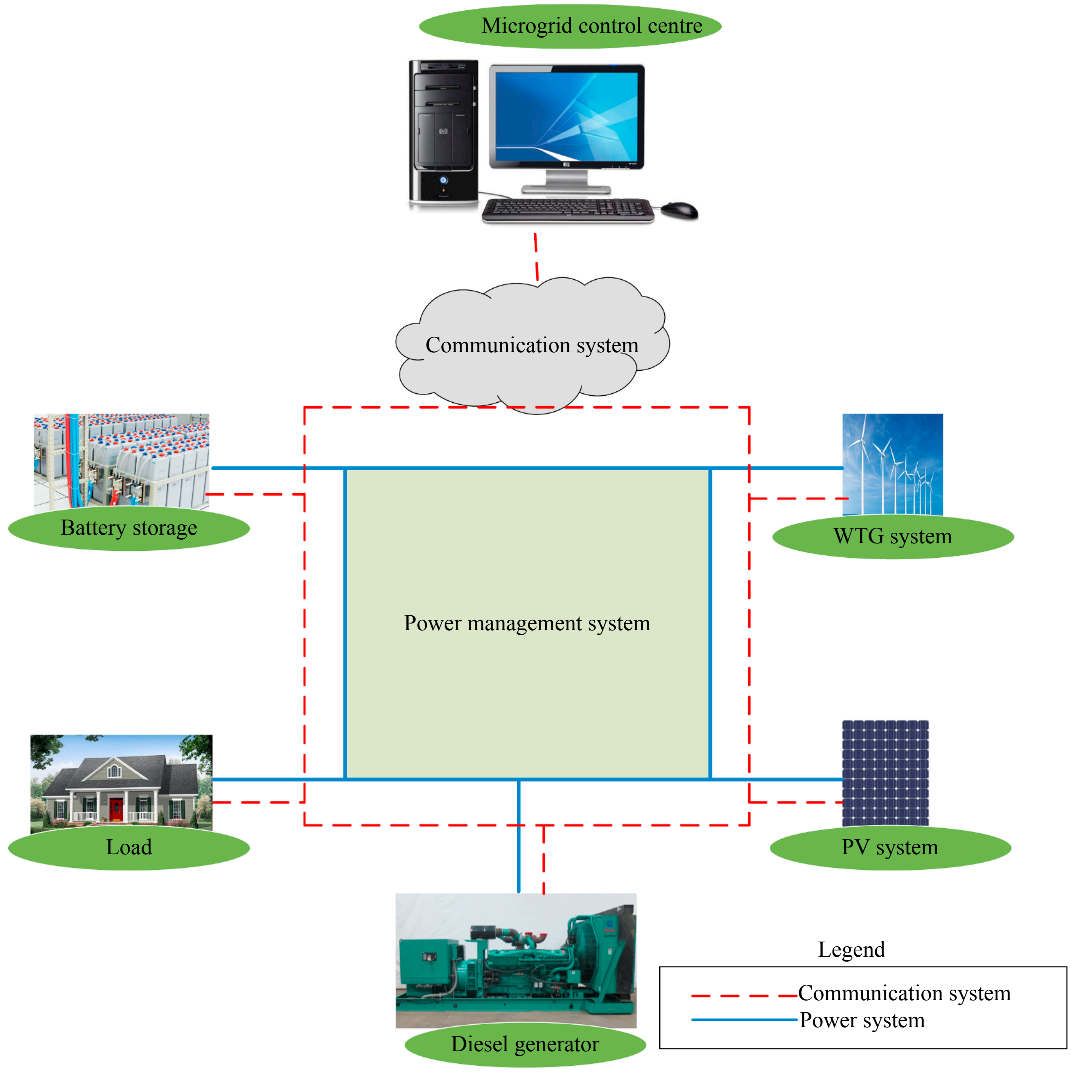

Fig. 1. Schematic diagram of a microgrid system.

work is presented in Eq. (5). The power output of the WTG depends on the wind speed at the hub height, geographical location and the operating characteristic of the WTG. The power generated ($P_{wtg}(v(t))$) by the WTG at time t can be expressed as [54]:

$$P_{wtg}(v(t)) = \begin{cases} 0 & v(t) < v_{ci} \\ a \times v^k - b \times P_r & v_{ci} \leqslant v(t) \leqslant v_r \\ P_r & v_r \leqslant v(t) \leqslant v_{co} \\ 0 & v(t) > v_{co} \end{cases} \quad (5)$$

where $a = \frac{P_r}{(v_r^k - v_{vci}^k)}$, $b = \frac{v_{ci}^k}{(v_r^k - v_{ci}^k)}$ and k is the Weibull shape parameter.

The overall power produced by the WTG can be expressed as:

$$P_{wtg}^t(t) = N_{wtg} \times P_{wtg}(v(t)) \quad (6)$$

where N_{wtg} is the number of the WTG units.

The wind speed at a reference height can be estimated by utilizing Eq. (7) [55]:

$$v = v_r \left(\frac{H_{hub}}{H_r} \right)^{\alpha} \quad (7)$$

where v is the wind speed at the hub height (H_{hub}), v_r is the wind speed at reference height (H_r) and α is the power law exponent that signifies the ground surface friction co-efficient.

2.4. Modelling of photovoltaic system

Solar energy is directly converted to electric power with the utilization of the PV panels for various applications in the microgrid systems [53]. The PV system can be connected in parallel and series configurations to meet the power demand of the consumers at time t. The operation of the PV system varies with time owing to the changes in the solar irradiation conditions, temperature, location, weather conditions and load pattern [12]. The output power of each PV panel at time t can be expressed as [56]:

$$P_{pv}(t) = A_{pv} \times I_{pv} \times \eta_{pv} \quad (8)$$

where A_{pv} is the area of the PV module (m^2), I_{pv} is the solar irradiation incident on the PV system (kWh/m^2), η_{pv} is the efficiency of the PV system and P_{pv} is the hourly power generated by the PV system.

The overall power generated by the PV system is given as:

$$P_{pv}^t(t) = N_{pv} \times P_{pv}(t) \quad (9)$$

where N_{pv} is the number of the PV panels.

3. Problem formulation

The first component of the objective function is aimed at minimizing the cost of energy, lifecycle cost, lifecycle GHG emission cost

Fig. 2. Proposed microgrid system.

and annual cost of load loss while satisfying the microgrid system constraints and the consumer's power demand. The second component of the objective function is also formulated to maximize the overall benefits of the PV, WTG and ESS in the proposed microgrid system as shown in Fig. 2. In this Section, the objective function and constraints of the proposed microgrid are expressed as follows:

$$F = \min \sum_{i=1}^{n} (obj1 - obj2) \tag{10}$$

where obj1 and obj2 are the first and second components of the objective function.

The first component of the objective function that is characterized with numerous problems is expressed in Eq. (11) as:

$$obj1 = \min \sum_{i=1}^{n} (LCC + COE + AC^{load}_{loss} + GEC_{total}) \tag{11}$$

where LCC is the lifecycle cost, AC^{load}_{loss} is the annual cost of load loss, GEC_{total} is the lifecycle GHG emission cost and COE is the cost of energy.

The second component of the objective function is based on the maximization of the environmental, economic and reliability benefits of utilizing green technologies in a microgrid system. It summarizes the expected aggregate of benefits made from integrating green technologies into the proposed microgrid system. This can be achieved by comparing the monetary values of the benefits with the base case study. For this reason, the second objective function is expressed in Eq. (12) as:

$$obj2 = -\min \sum_{i=1}^{n} (EC_{benefit} + IC_{benefit} + MC_{benefit} + GEC_{benefit} + FC_{benefit}) \tag{12}$$

where $EC_{benefit}$ is the electricity cost benefit, $IC_{benefit}$ is the annual cost of load loss benefit, $MC_{benefit}$ is the maintenance cost benefit, $GEC_{benefit}$ is the greenhouse gas emission cost benefit and $FC_{benefit}$ fuel cost benefit respectively.

The aforementioned benefits are further explained in Eq. (13) as:

$$obj2 = -\min\left(\sum_{i=1}^{n}\sum_{j=1}^{m} x_{j,i} - \sum_{i=1}^{n}\sum_{j=1}^{m} y_{j,i}\right) \tag{13}$$

where $x_{1,i}$, $x_{2,i}$, $x_{3,i}$, $x_{4,i}$and $x_{5,i}$denote the base electricity cost, cost of load loss, maintenance cost, greenhouse gas emission cost and fuel cost before integration of WTG, PV and ESS into the system. While $y_{1,i}$, $y_{2,i}$, $y_{3,i}$, $y_{4,i}$and $y_{5,i}$ are the new electricity cost, cost of load loss, maintenance cost, greenhouse gas emission cost and fuel cost after integration of WTG, PV and ESS into the system.

The objective function of the proposed microgrid is represented with the combination of the Eqs. (11) and (12) as shown in this subsection. Hence, the multi-objective function of the system is characterized by the summation of two equations that is expressed as:

$$Obj_1 + Obj_2 = \min \left\{ \begin{array}{c} \sum_{i=1}^{n} (LCC + COE + AC_{loss}^{load} + GEC_{total}) - \\ \sum_{i=1}^{n} (EC_{benefit} + IC_{benefit} + MC_{benefit} + GEC_{benefit} \\ + FC_{benefit}) \end{array} \right\} \tag{14}$$

$$= \min \left\{ \begin{array}{c} \sum_{i=1}^{n} (LCC + COE + AC_{loss}^{load} + GEC_{total}) - \\ \left(\sum_{i=1}^{n} \sum_{j=1}^{m} x_{j,i} - \sum_{i=1}^{n} \sum_{j=1}^{m} y_{j,i} \right) \end{array} \right\}$$

3.1. Constraint functions

The multi-objective functions proposed in this work is subject to the constraints that are meant to operate within their specific minimum and maximum values. The power balance, SOC of the ESS and power generating limits are considered in the proposed microgrid system. The system constraints considered in this study are presented as follows.

3.1.1. Power balance constraint

The power produced from various sources such as the diesel generator, PV, WTG and ESS units are designed to meet system load demands. This relationship is expressed in Eq. (15) as:

$$\sum_{z=1}^{N_{load}} P_L(z,t) = \sum_{i=1}^{N_{gen}} P_{gen}(i,t) + \sum_{j=1}^{N_{pv}} P_{pv}(j,t) + \sum_{k=1}^{N_{wtg}} P_{wtg}(k,t) - \sum_{m=1}^{N_{ess}} P_{ess}^{ch}(m,t) + \sum_{n=1}^{N_{ess}} P_{ess}^{dis}(n,t) \tag{15}$$

where $P_{gen}(i,t)$ is the power output of diesel generator during time t, $P_{pv}(j,t)$ is the power generated by PV at time t and $P_{wtg}(k,t)$ is the power generated by WTG at time t while $P_{ess}^{ch}(m,t)$ and $P_{ess}^{dis}(n,t)$ are the power charge and discharge by the electric storage system at time t. $P_L(z,t)$ is the total power demand at time t. In addition to this, $N_{wtg}N_{pv}$, $N_{ess}$and N_{gen} depict the number of WTG, PV, ESS and diesel generator units utilized in the microgrid while N_{load} denotes the number of load points.

3.1.2. Power output constraints

The output power of the WTG, PV, ESS and diesel generator at time t should be able to operate within their specific minimum and maximum limits. The output power of each generation source has minimum and maximum limits as expressed in Eq. (16):

$$\left\{ \begin{array}{c} P_{gen}^{\min}(i,t) \leqslant P_{gen}(i,t) \leqslant P_{gen}^{\max}(i,t) \\ P_{pv}^{\min}(j,t) \leqslant P_{pv}(j,t) \leqslant P_{pv}^{\max}(j,t) \\ P_{wtg}^{\min}(k,t) \leqslant P_{wtg}(k,t) \leqslant P_{wtg}^{\max}(k,t) \\ P_{ess}^{ch,\min}(m,t) \leqslant P_{ess}^{ch}(m,t) \leqslant P_{ess}^{ch,\max}(m,t) \\ P_{ess}^{dis,\min}(n,t) \leqslant P_{ess}^{dis}(n,t) \leqslant P_{ess}^{dis,\max}(n,t) \end{array} \right. \tag{16}$$

3.2. Algorithm proposed in the proposed microgrid

The non-linear optimization problem of a microgrid system can be solved by utilizing the fmincon function in MATLAB environment. Owing to this, the fmincon solver in the MATLAB R2016b optimization toolbox is proposed in this research work to solve the multi- objective problems. The objective function of the study can be expressed as:

$$\min f(X) \tag{17}$$

subject to

$$\left\{ \begin{array}{l} Ax \leqslant b\,(linear\ \ inequality\ constra\,\mathrm{int}), \\ A_{eq} = b_{eq}\,(linear\ equality\ constra\,\mathrm{int}), \\ C(x) \leqslant 0\,(nonlinear\ inquality\ consra\,\mathrm{int}), \\ C_{eq}(x) \leqslant 0\,(nonlinear\ equality\ contsra\,\mathrm{int}), \\ C_{eq}(x) = 0\,(nonlinear\ equality\ constra\,\mathrm{int})\,and \\ L_b \leqslant x \leqslant U_b\,(lower\ and\ upper\ bounds) \end{array} \right. \tag{18}$$

4. Cost assessment of the proposed microgrid system

The lifecycle cost analysis is introduced in this research work due to the fact that it can be utilized to compare the expenses of various options to achieve a specific level of sustainability. The application of the lifecycle cost analysis in a power system provides numerous benefits for the power utilities such as maximization of the profitability and minimization of the investment cost of the power system. The lifecycle cost as applicable in this study is used to evaluate the cost incurred throughout the lifecycle of the microgrid, irrespective of the cost incurred during the disposal stage and manufacturing stage that includes materials, labour and variable overheads. The values of the lifecycle cost as estimated in this research work, consider the present value of replacement cost, present value of the operation and maintenance cost and capital cost [19].

4.1. Capital cost

Capital cost is the cost incurred to purchase the major components that constitute a microgrid system as shown in Fig. 2. Moreover, capital cost is needed to bring a microgrid system to a commercially operable status. The capital cost for the entire system is the sum of the procurement costs estimated for each component of the microgrid system. The capital cost is one of the key components of LCC and it can be expressed as:

$$Cap_{init} = \{x_1 C_{gen} Y_{gen} + x_2 C_{pv} Y_{pv} + x_3 C_{wtg} Y_{wtg} + x_4 C_{ess} Y_{ess} + x_5 C_{Inv} Y_{inv}\} \tag{19}$$

where C_{gen}, C_{pv}, C_{wtg}, C_{ess} and $C_{inv}$are the costs of the diesel generator (per kW), PV (per kW), WTG (per kW), ESS (per unit) and inverter (inv) (per kW). While x_1, x_2, x_3, x_4 and x_5 are the ratings of the diesel generator, PV, WTG, ESS and inverter respectively.

The decision variables of the generating units and other components are defined as follows:

$$Y_{gen} = \begin{cases} 1 & Application\ of\ diesel\ generator\ \ in\ the\ system \\ 0 & Otherwise \end{cases} \tag{20}$$

where Y_{gen} is the decision variable for diesel generator.

$$Y_{pv} = \begin{cases} 1 & Application\ of\ PV\ in\ the\ system \\ 0 & Otherwise \end{cases} \tag{21}$$

where Y_{pv} is the decision variable for the PV.

$$Y_{wtg} = \begin{cases} 1 & Application\ of\ \ WTG\ in\ the\ system \\ 0 & Otherwise \end{cases} \tag{22}$$

where Y_{wtg} is the decision variable for the WTG.

$$Y_{ess} = \begin{cases} 1 & Application\ of\ ESS\ in\ the\ system \\ 0 & Otherwise \end{cases} \tag{23}$$

where Y_{ess} is the decision variable for the ESS.

$$Y_{inv} = \begin{cases} 1 & Application\ of\ inverter\ \ in\ the\ system \\ 0 & Otherwise \end{cases} \tag{24}$$

where Y_{inv} is the decision variable for the inverter.

4.2. Cost of replacement

The cost of replacement of the major components that constitute the microgrid system is considered during their life cycles. The replacement cost is assessed as the final step of the LCC analysis of a microgrid system. Owing to this, the present estimation of all expenses of replacement of the components of the microgrid throughout the lifecycle of the project is assessed. The present cost of replacement of a microgrid system can be expressed as follows:

$$C_{rep} = \left(\frac{1+f}{1+i}\right)^{proj}\{C_{rep}^{gen}C_{unit}^{gen}Y_{gen} + C_{rep}^{pv}C_{unit}^{pv}Y_{pv} + C_{rep}^{wtg}C_{unit}^{wtg}Y_{wtg} + C_{rep}^{ess}C_{unit}^{ess}Y_{ess} + C_{rep}^{inv}C_{unit}^{inv}Y_{inv}\} \tag{25}$$

where i is the real interest rate, f is the inflation rate of the component replacement, $proj$ is the lifetime of the components in years, C_{unit}^{gen}, C_{unit}^{pv}, C_{unit}^{wtg}, C_{unit}^{ess} and C_{unit}^{inv} are the unit components cost for the diesel generator, PV, WTG, ESS and inverter and C_{rep}^{gen}, C_{rep}^{pv}, C_{rep}^{wtg}, C_{rep}^{ess} and C_{rep}^{inv} are the nominal capacity of the replacement cost for the above-mentioned components.

4.3. Operation and maintenance costs

The O&M costs of each component of the proposed microgrid are part of the LCC. The O&M costs can be estimated for each component based on its expected useful life. The O&M costs that are associated with a microgrid system throughout the lifecycle of the system also include the cost of fuel of the diesel generator that carries the largest percentage of the operating cost of the reciprocating engine. The O&M costs that vary with the utilization of the microgrid system depend on the inflation rate and interest rate. In this research work, the inflation rate and interest rate for each complement of the proposed microgrid system are assumed to be 4% and 8% [19]. It can be expressed in Eq. (26) as:

$$C_{o\&m} = \begin{cases} \left[\frac{(1+f)}{(i-f)}\right]\left[1-\left(\frac{1+f}{1+i}\right)^{proj}\right]\{C_{o\&m}^{gen}Y_{gen} + C_{o\&m}^{pv}Y_{pv} + C_{o\&m}^{wtg}Y_{wtg} + C_{o\&m}^{ess}Y_{ess} \\ \quad + C_{o\&m}^{inv}Y_{inv}\}, \ for\ i \neq f \\ \{C_{o\&m}^{gen}Y_{gen} + C_{o\&m}^{pv}Y_{pv} + C_{o\&m}^{wtg}Y_{wtg} + C_{o\&m}^{ess}Y_{ess} + C_{o\&m}^{inv}Y_{inv}\} \times proj, \ for\ i = f \end{cases} \tag{26}$$

where $C_{o\&m}^{gen}$, $C_{o\&m}^{pv}$, $C_{o\&m}^{wtg}$, $C_{o\&m}^{ess}$ and $C_{o\&m}^{inv}$ are the annual operation and maintenance costs of the diesel generator, PV, WTG, ESS and inverter respectively.

4.4. Cost of energy

The annualized lifecycle cost (ALC) and COE can be estimated from the overall LCC and annual energy production (AEP) as follows [2]:

$$ALC = \left\{\frac{LCC}{\left[\frac{(1+f)}{(i-f)}\right]\left[1-\left(\frac{1+f}{1+i}\right)^{proj}\right]}\right\} \tag{27}$$

$$COE = \left\{\frac{ALC}{AEP}\right\} \tag{28}$$

4.5. Greenhouse gas emission cost

The total GHG emission cost throughout the lifetime of the proposed microgrid system is the summation of the hourly Sulphur dioxide (SO_2), Nitrogen oxide (NO_x) and Carbon dioxide (CO_2) emissions. The life cycle GHG emission cost of a diesel generator can be presented in Eq. (29) as:

$$GEC_{total} = \left[\frac{(1+f)}{(i-f)}\right]\left[1-\left(\frac{1+f}{1+i}\right)^{proj}\right]\left\{\sum_{i=1}^{m}\sum_{j=1}^{n}PF_jE_{ij}P_i\right\} = \left[\frac{(1+f)}{(i-f)}\right]\left[1-\left(\frac{1+f}{1+i}\right)^{proj}\right]\left\{\sum_{i=1}^{m}\sum_{j=1}^{n}PF_jP_i(CO_{2,Gi}(t) + SO_{2,Gi}(t) + NO_{x,Gi}(t))\right\} \tag{29}$$

where P_i is the power produced by the diesel generator, PF_j is the externality costs of emission type j of the diesel generator unit, m = emission types CO_2, SO_2 and NOx. While $CO_{2,Gi}(t)$, $SO_{2,Gi}(t)$and $NO_{x,Gi}(t)$ are the emissions from the diesel generator source (G_i) at tth hour. E_{ij} is the emission factor of the diesel generator unit i and emission type j and n is the number of diesel generators.

4.6. Cost of electricity consumption

The annual cost of electricity consumption (EC) is introduced in this research work to evaluate the economic benefits of penetration RERs and ESS into a microgrid system.

$$EC = \sum_{t=1}^{n} COE \times E_i(t) \tag{30}$$

where $E_i(t)$is the energy at time t

5. Reliability assessment of the proposed microgrid system

The power systems have been observed globally to be changing their structures from the vertically integrated organization to an unbundled one. This requires sudden improvement in the performance and efficiency of the power system as a result of uninterrupted power demand at the load centres. Therefore, different measures must be put in place by the utilities to ensure their networks are able to withstand the congestion that is associated with the increase in the power demand. One of the most significant performance indicators that need considerable attention is the reliability evaluation of a power system. The reliability assessment techniques can be used to investigate the effect of green technologies on the power system adequacy. The impact of green technologies is relatively important on the load centres and the reliability performance of the power system. This has necessitated various methods to be used by the utilities to carry out the reliability evaluation of a microgrid system. The reliability of a power system is measured in the terms of its ability to perform the basic function.

5.1. Reliability indices

The reliability benefits of utilizing RERs in a microgrid system can be evaluated with the application of the reliability indices. The reliability indices also provide useful information about the system capability and performance. The concepts proposed in this research work allow the reliability indices to be used for the evaluation of the cost that is associated with the failure of the utilities to provide a reliable power supply. Several reliability indices such as EENS, LOLE and LOLP are introduced in this study as the most commonly utilized indices for the reliability evaluation of the generating systems. The reliability indices can be used by the utilities to estimate the overall adequacy of their systems and project future power demand based on the results obtained from the reliability assessment. The reliability indices are briefly discussed as follows.

5.1.1. Loss of load expectation

The LOLE is the number of days (hours) in a predefined period in which the daily peak load surpasses the accessible generating capacity [57]. The LOLE is a metric that can be used to measure the security of a power supply and to set a reliability standard by the power regulatory commission of each country. The value of LOLE can be estimated by using Eq. (31) [58]:

Table 2
Technical specifications and economic parameters of the microgrid system [4,5,8].

Description	Replacement cost	Capital cost	Maintenance cost	Lifetime	Other operating parameters
Diesel generator	300 $/kW	300 $/kW	0.01258 $/kWh	25,000 h	Capacity = 48 kW Model = DNAC a = 0.4333 b = 0.2333 c = 0.007 Diesel fuel price = $0.91/litre
Wind turbine	300 $/kW	300 $/kW	20 $/kW/year	25 yrs	Capacity = 500 W Model number = H.27–500 W v_{ci} = 3 m/s, v_r = 11 m/s, v_{co} = 25 m/s, swept area = 5.73 m^2, generator efficiency = 0.78 and wind energy utilize ratio = 0.48
PV	630 $/kW	630 $/kW	10 $/kW/year	25 yrs	Capacity = 300 W Model number = STP 300–24/Ve maximum power point voltage = 35.9 V, maximum power point current = 8.36 A, nominal cell operating temperature (NOCT) = 45 ± 2 °C, voltage temperature coefficient = −0.33%/°C, current temperature coefficient = 0.067%/°C, short circuit current = 8.83A, open circuit voltage = 44.5 V and operating temperature −40 °C to 85 °C, module efficiency = 15.5% and dimension of the PV panel = 1956 mm × 9992 mm × 40 mm
ESS	300 $/battery	300 $/ battery	10 $/ESS/year	5 yrs	ESS = 4 kWh or 84 Ah ESS max SOC = 95% ESS minimum SOC = 40% ESS discharging efficiency = 100% ESS Charge efficiency = 80%
Converter	300 $/kW	300 $/kW	3 $/kW	15 yrs	

$$LOLE = \sum_{k=1}^{n} p_k \times t_k \tag{31}$$

where p_k is the individual probability of capacity outage, n is the number of capacity outage state in excess of the reserve and t_k is the time at which the loss load occurs.

The Eq. (31) can further be modified by using the cumulative probability as expressed in Eq. (32).

$$LOLE = \sum_{k=1}^{n} P_k \times (t_k - t_{k-1}) \tag{32}$$

where P_k is the cumulative outage probability for capacity outage.

5.1.2. Expected energy not supplied

The EENS is the expected unsupplied energy in a year owing to generation unavailability or inadequacy or lack of primary energy [59]. The outage with a probability p_k causes an energy curtailment of E_k as presented in Eq. (33) as [57]:

$$EENS = \sum_{k=1}^{n} P_k \times E_k \tag{33}$$

5.1.3. Loss of load probability

The LOLP is the probability that power demand exceeds generation capacity over a certain period of time [58]. The LOLP analysis is performed on hourly or daily in a year during which customer disconnection is expected to determine the value of the generating units that need to be added to the existing generation capacity as a measure to meet the reliability target or enhance the reliability of the system. It can also be used as a standard by the utilities to evaluate the number of days in a year in which the generation units won't have the capacity to meet the daily peak. The mathematical formula for estimation of LOLP is presented in equation (34) as:

$$LOLP = \sum_{j} P\,[C_A = C_j] \times P\,[L > C_j] = \sum_{j} P_j t_j \tag{34}$$

where P is the probability, C_A is the available generation capacity, L is the expected load, P_j is the probability of capacity outage, C_j is the remaining generation capacity and t_j is percentage of time when the load exceeds C_j.

5.1.4. Annual cost of load loss

The annual cost of load loss is used by the utilities and the energy regulatory commission to monetize the consequence of power interruption [5]. It provides useful economic information to the customers about the costs that will be incurred during the periods of incremental power demand that cannot be met by the utilities. This indicates that the annual cost of load loss can be used by the utilities to assess the economic efficiency and the reliability capability of their networks. The values of the cost of customer dissatisfaction (C_{loss}) depend on the classes of the customer under consideration based on the duration of an outage, the time of day, the season of an outage and the frequency of an outage. The values of (C_{loss})are in the range of 5–40 $/kWh for industrial customers and 2–12 $/kWh for residential customers [60]. The value of 5.5 $/kWh that is used in this study is based on South Africa benchmarks. The AC_{loss}^{load} is a product of EENS and (C_{loss})as presented in Eq. (35) as [5]:

$$AC_{loss}^{load} = \sum_{i=1}^{n} EENS_i \times C_{loss,i} \tag{35}$$

5.1.5. Forced outage rate

The forced outage rate (FOR) is one of the most important input quantities that is required in the reliability analysis of power generation adequacy [58]. The forced outage rate of any component in a microgrid system is the likelihood that the component won't be available for service when required. In this research work, FOR for each generating unit in the proposed microgrid is taken into consideration.

$$FOR = \frac{\sum (down\_time)}{\sum (down\_time) + \sum (up\_time)} \tag{36}$$

6. Technical specifications, cost parameters and reliability indices of the microgrid system

The proposed technique is implemented in the MATLAB programming environment by using MATLAB software version R2016b on Intel (R) Core(TM) i3-6100 CPU @ 3.70 GHz and installed memory (RAM) 4 GB. The microgrid system is modelled by using the technical specifications, cost parameters and reliability indices of each component of the system as shown in Tables 2 and 3. The data are used to optimize

Table 3
Reliability indices of the power system.

Description	Failure rate per year	FOR	MTTF (h)	MTTR (h)
Diesel generator	9.3	0.06	940	60
Wind turbine	4.6	0.04	1920	80
PV	3	0.03	2910	90
ESS	4.6	0.04	1920	80

the objective functions of this research work as discussed in Section 3. The technical and financial details as presented in Table 2 are used to assess the economic viability of green technologies in a microgrid system. The reliability indices and investment costs can be utilized to evaluate the optimal operation of a power system. The developed evaluation model is applied in the proposed microgrid system by using the technical specifications, reliability indices and cost parameters to evaluate the LCC, COE, AC_{loss}^{load}, GEC_{total} and overall benefit of the WTG, PV and ESS.

7. Simulation results and discussions

The reliability, environmental and economic evaluation of a microgrid system with the incorporation of the PV, WTG and ESS can be carried out by utilizing the operation parameters presented in Tables 3 and 4. The green technologies are used in this research work to surmount the trend of financial impacts of power outages and to reduce the lifecycle costs of a microgrid system. The results obtained from the study are analysed to determine the impacts of green technologies on the optimal operation of the proposed microgrid system. The effect of the above mentioned generating units can be used as a benchmark to assess their reliability, environmental and economic benefits in a microgrid system. The optimization method discussed in Section 3 is applied in this research work by utilizing the configurations presented in Table 4. The results obtained from six case studies of the proposed microgrid system are analyzed and discussed based on the economic, environmental and reliability performances.

The impacts of green technologies in a microgrid system are examined in this Section based on the values of LCC, COE, AC_{loss}^{load}, GEC_{total} and overall benefit for each case study as presented as follows:

Case study 1: In this case study, the diesel generator is designed in such a way to meet the load demand of the consumers, since no other power source is available. This demonstrates that the power demand of the consumers is met by the diesel generator that uses diesel fuels. The microgrid system behaviour based on the configuration of this case study is shown in Figs. 3a–3b. This indicates that 100% of the power demand by the consumers depends on the operation of the diesel generator with a lifecycle cost of $2.64 million, a COE of 0.235 $/kWh, a GEC_{total} of $0.583 million for the lifecycle of the microgrid and AC_{loss}^{load} of 258. 2151 $/yr as shown in Table 5 and Figs. 4a–4e. It is observed from the results that the cost-effectiveness of the diesel generator depends on the daily power demand of the consumers since there is no alternative to complement its operation. The environmental performance that is assessed in case study 1 produces 3.2 kg of CO_2, 3.26 kg of NO_x and 1.75 kg of SO_2 over a lifecycle of a microgrid system which is estimated to be 25 years. The high values of the GHG emissions obtained in this case study show the environmental implications of using diesel generator in the power system as presented in Figs. 5a–5c and Table 6.

Moreover, the reliability assessment of the proposed microgrid system is also carried out with the following results: EENS = 46.9485 kWh/yr, LOLE = 34.1081 h/yr and LOLP = 0.003904. The reliability of the microgrid system under consideration can be improved with the integration of the WTG, PV and ESS as presented in Table 7. The results obtained in case study 1 show that it is not economically and environmentally sustainable to use diesel generator alone to meet the load demand of rural residents in a situation where there is an availability of solar and wind resources because of the high values of COE, LCC, GEC_{total} and AC_{loss}^{load}. This has justified the reason to limit the utilization of the diesel generator and maximize the application of green technologies in a microgrid system. Therefore, the RERs and ESS are widely utilized in the remote areas because of economic, environmental and reliability benefits.

Case study 2: This case study utilizes the diesel generator, PV, WTG and ESS with their respective operating parameters to meet the consumer load demand. The aforementioned generating units are running simultaneously to supply electrical power to the load points. The contribution of this case study and the behaviours of each generating unit for 24 h are presented in Fig. 6. It can be established from Fig. 6 that power generated by the diesel generator has been reduced owing to the integration of renewable energy distributed technologies into the system. The performance of the system and the cost savings as presented in Table 5 and Figs. 4a–4e show that the key operating parameters of the proposed microgrid system have improved considerably when compared with a circumstance where a diesel generator is utilized alone to meet the load demand, with a lifecycle cost of $2.42 million, a COE of 0.2161 $/kWh, a GEC_{total} of $0.548 million for the lifecycle of 25 years and $AC_{loss}^{load}$of 74,5041 $/yr. The values of COE, LCC, GEC_{total} and AC_{loss}^{load} obtained in this case study can further be minimized to a specific level with the incorporation of green technologies.

The environmental performance assessed in this case study produces 3.01 kg ofCO_2, 3.0686 kg of NO_x and 1.65 kg of SO_2 throughout the lifecycle of a microgrid system that is estimated to be 25 years. Moreover, the emission performance of the system is analyzed by comparing the quantity of the lifecycle emissions of case study 1 with case study 2 that uses a combination of RERs and diesel generator. The utilization of RERs and ESS units has reduced the quantity of GHG emission generated by the diesel generator as presented in Figs. 5a–5c and Table 7. The comparative analysis of GHG emission of the proposed microgrid system has substantiated that more cost savings can be accomplished with the integration of green technologies. The generating adequacy of a power system is the ability of the system generation capacity to meet the load requirements. This objective can be achieved by expansion of the generating capacity of a power system by adding new units based on the technical and financial considerations. The performance indicators used for evaluation of a generation adequacy in this case study show that the reliability indices have improved with the following values: EENS = 13.5462 kWh/yr, LOLE = 6.9156 h/yr and LOLP = 7.9162×10^{-4}. The reliability performance of the system has been improved significantly based on the additional number of PV, WTG and ESS units. Moreover, the overall benefit for this case study is 2.954×10^4 $/yr. This shows that the utilization of green technologies has a substantial effect on the economic, environmental and reliability benefits performance of a microgrid system.

Case study 3: To further assess the economic, environmental and reliability performance of green technologies in a microgrid system, additional units of the PV, WTG and ESS are incorporated into the system as shown in Table 4. Similarly, the power produced by each generating unit as shown in Fig. 7 indicates that power output of the diesel generator has reduced in the presence of the additional number of the PV, WTG and ESS units. It is observed that case study 2 presents a better economic performance when compared with the case study 1 in terms of a lifecycle cost of $2.25 million, a COE of 0.2002 $/kWh, a

Table 4
Configurations of the case study [5].

Description	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case study 6
Diesel Generator (kW)	48	48	48	48	48	48
PV (kW)	0	3	6	9	12	15
WTG (kW)	0	1	2	9	12	15
ESS (kW)	0	1	1	3	4	5

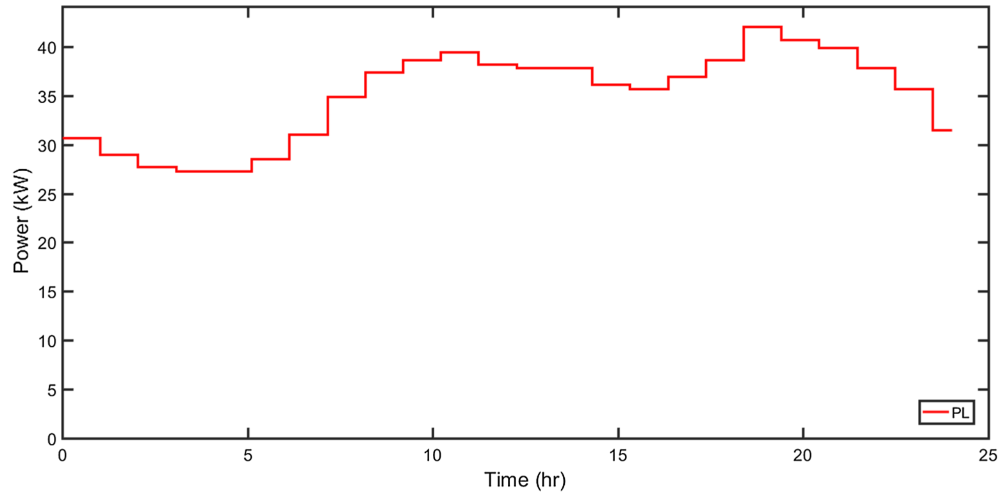

Fig. 3a. Case study 1: variation of load demand.

GEC_{total} of \$0.5171 million for the lifecycle of 25 years and AC_{loss}^{load} of 17.5456 \$/yr as presented in Table 5 and Figs. 4a–4e. The cost savings obtained in this case study as presented in Figs. 4d–4e show that RERs and ESS have increased the economic performance of the microgrid system. Moreover, to demonstrate the impacts of green technologies on the environmental performance of the system, it is observed that the lifecycle CO_2, NO_x and SO_2 emissions for this case study are 2.84 kg, 2.904 kg and 1.56 kg respectively. The impacts of the aforementioned generating units on the environmental benefits as presented in Figs. 5a–5c and Table 6 confirm their practical and workable applications in a microgrid system. Similarly, this has also improved the reliability performance of the proposed power system with the following values, i.e. EENS = 3.1901 kWh/yr, LOLE = 0.87634 h/yr and LOLP = 10.031×10^{-5}. The results obtained from this case study as presented in Table 7 have validated the impacts of RERs and ESS on the reliability of the proposed microgrid system. The value of the overall benefit obtained in this case study is 5.46×10^4 \$/yr, this demonstrates that the application of the PV, WTG and ESS has substantiated the reliability, economic and environmental benefits of green technologies in a microgrid system.

Case study 4: The configuration of this case study and the power generated from each unit are presented in Fig. 8. It is observed from Fig. 8 that the power produced by the diesel generator has reduced considerably when compared with case study 1. Similarly, the results obtained from this case study have further proved that the integration of additional units of RERs and ESS into a microgrid system has improved the performance indicators of the proposed microgrid such lifecycle cost, COE, GEC_{total} and AC_{loss}^{load} to \$1.78 million, 0.1589 \$/kWh, \$0.429 million and 0.074 \$/yr as presented in Table 5 and Figs. 4a–4e. The economic performance of this case study has improved based on the cost savings analysis that is presented in Figs. 4d–4e. Moreover, the environmental performance of this case study produces 2.36 kg of CO_2, 2.40 kg of NO_x and 1.29 kg of SO_2 over a lifecycle of the microgrid system. The application of RERs and ESS in this case study has reduced the quantity of GHG emissions generated by the diesel generator to a certain extent as presented in Figs. 5a–5c and Table 6. Similarly, the incorporation of RERs and ESS has a significant effect on the reliability performance of a power system as shown in Table 7. This has further

Table 5
Economic analysis of the case studies.

Case study	COE (\$/kWh)	LCC (\$)	LCC Emission cost (\$)	Interruption Cost (\$/yr)	Benefit (\$/yr)
1	0.235	2.64×10^6	5.83×10^5	258.2151	0
2	0.2161	2.42×10^6	5.48×10^5	74.5041	29,460
3	0.2002	2.25×10^6	5.17×10^5	17.5456	54,570
4	0.1589	1.78×10^6	4.29×10^5	0.074	119,540
5	0.1383	1.55×10^6	3.79×10^5	0.0018	152,520
6	0.1197	1.34×10^6	3.29×10^5	2.47E-05	182,650

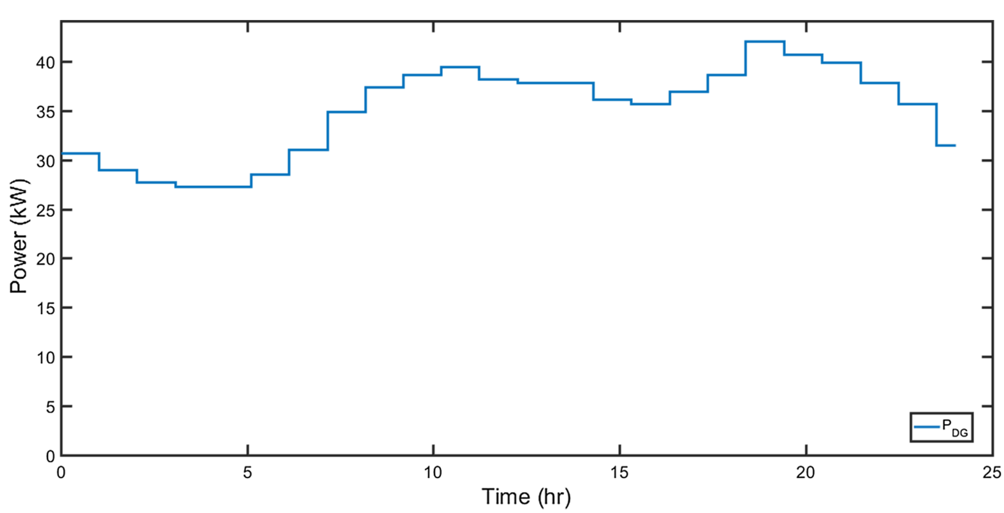

Fig. 3b. Case study 1: variations of power from the diesel generator.

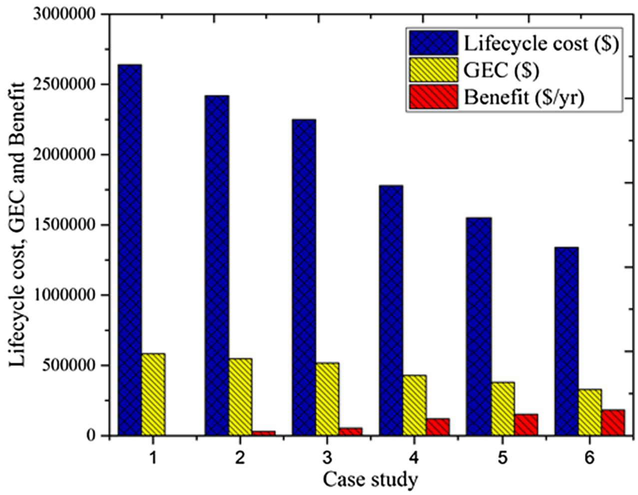

Fig. 4a. The economic performance of the proposed microgrid system.

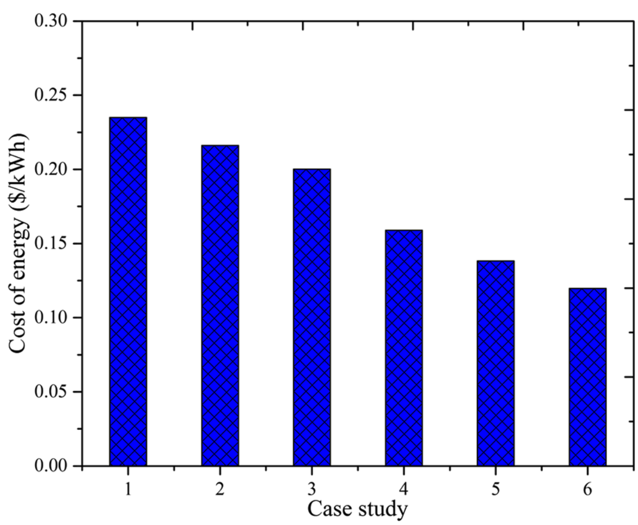

Fig. 4b. Comparison of cost of energy for different case studies.

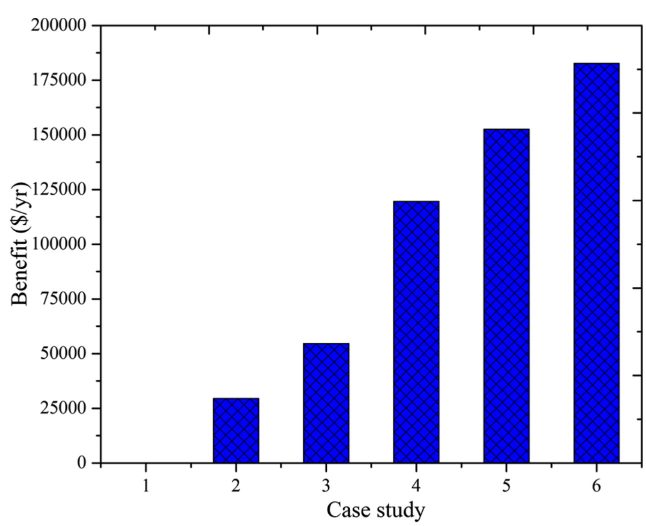

Fig. 4c. Overall benefit analysis of a microgrid system.

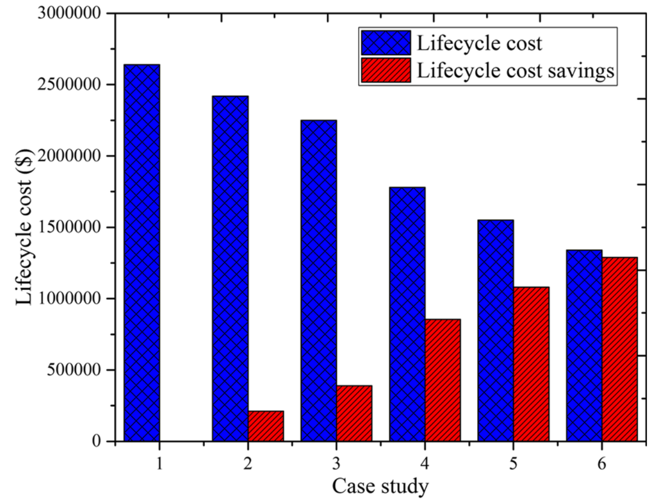

Fig. 4d. Lifecycle analysis of a microgrid system.

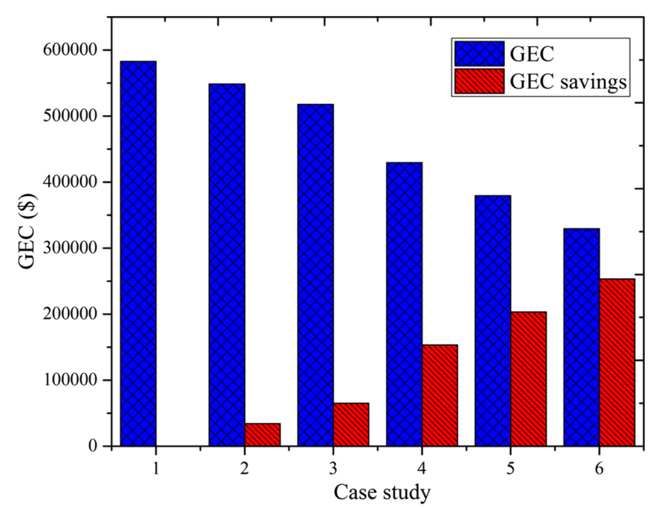

Fig. 4e. Comparison of lifecycle GHG emission cost for different case studies.

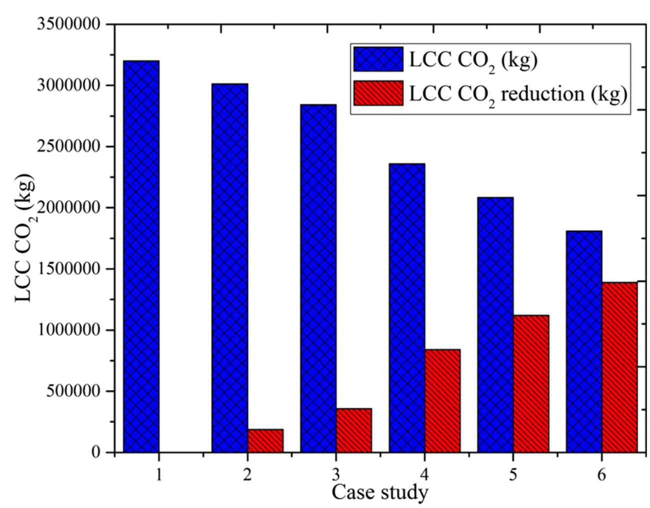

Fig. 5a. Impacts of PV, WTG and ESS on CO_2 reduction of the proposed microgrid system.

enhanced the reliability indices of the proposed microgrid system such as EENS, LOLE and LOLP with the following values: 1.3455×10^{-2} kWh/yr, 4.982×10^{-3} h/yr and 5.70×10^{-7}. The values of the reliability performance indicators obtained in case study 4 are more financially feasible when compared with using only the reciprocating engine to supply the entire power system. The overall benefit obtained

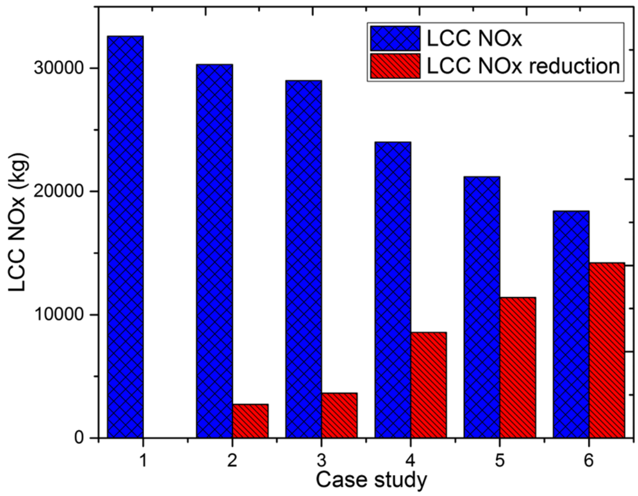

Fig. 5b. Impacts of PV, WTG and ESS on NO_x reduction of the proposed microgrid system.

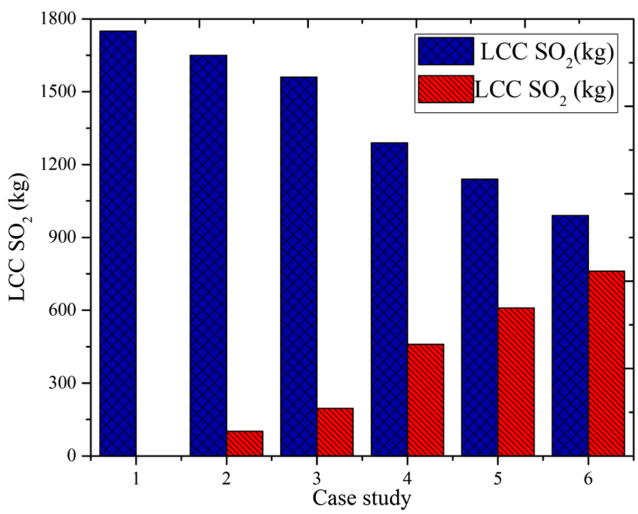

Fig. 5c. Impacts of PV, WTG and ESS on SO_2 reduction of the proposed microgrid system.

in this case study is 1.20×10^5 $/yr. This indicates that the reliability, economic and environmental benefits of the system have improved with the incorporation of the ESS and RERs.

Case study 5: In case study 5, the power generated by the diesel generator has witnessed a rapid reduction with the increase in numbers of RERs and ESS units as shown in Fig. 9. It can be established from Table 5 and Figs. 4a–4e that the values of lifecycle cost, COE, GEC_{total} and AC_{loss}^{load} have reduced to $1.55 million, 0.1383 $/kWh, $0.379 million and 0.0018 $/yr. The economic performance of the system coupled with the cost savings as presented in Figs. 4d–4e has further proved a vital improvement in the performance of the proposed microgrid system. Similarly, the lifecycle quantities of CO_2, $NO_x$and SO_2 emissions generated by the diesel generator in this case study are 2.08 kg, 2.12 kg and 1.14 kg. This indicates that the values of GHG emissions have been reduced to a certain extent when compared with the case study 1 as presented in Figs. 5a–5c and Table 6. The incorporation of the additional number of RERs technologies and ESS units also enhances the reliability of the system with the following values: EENS = 4.478×10^{-4} kWh/yr, LOLE = 2.47×10^{-4} h/yr and LOLP = 2.8336×10^{-8}. The results presented in Table 7 for this case study show that the integration of renewable energy distributed technologies has brought a substantial improvement in the system reliability. Similarly, the overall benefit obtained in this case study is 1.53×10^5 $/yr. This demonstrates that the integration of the additional number of green technologies has made a microgrid system to be more technical, environmental and economic feasible.

Table 7
Reliability analysis of the case studies.

Case study	EENS (KWh/yr)	LOLE (h/yr)	LOLP
1	46.9485	34.1081	0.0039043
2	13.5462	6.9156	0.00079162
3	3.1901	0.87634	0.00010031
4	0.013455	0.004982	5.70×10^{-7}
5	0.000334	0.000142	1.63×10^{-8}
6	4.49×10^{-6}	2.46×10^{-6}	2.81×10^{-10}

Case study 6: In this case study, the integration of the additional number of the PV, WTG and ESS units into the proposed microgrid system has reduced the power output of the diesel generator as shown in Fig. 10. This indicates that the generation capacity and the reserve margin of the system have been increased and subsequently improved the key performance indicators. The application of the aforementioned generating units has reduced the values of lifecycle cost of the project for over a time horizon of 25 years, COE, GEC_{total} and AC_{loss}^{load} to $1.34 million, 0.1197 $/kWh, $0.329 million and 0.0000247 $/yr as presented in Table 5 and Figs. 4a–4e. The cost savings of this case study has further improved with the integration of additional units of RERs and ESS based on the results presented in Figs. 4d–4e. Moreover, it has reduced the lifecycle quantity of CO_2, $NO_x$and SO_2 emissions from the diesel generator to 1.81 kg, 1.84 kg and 9.90 kg respectively as presented in Figs. 5a–5c and Table 6. This shows that green technologies have positive impacts on the environmental performance of a microgrid system. The integration of the PV, WTG and ESS units into the proposed microgrid system has also improved the reliability indices of the system, such as EENS, LOLE and LOLP to 4.49×10^{-6} kWh/yr, 2.464×10^{-6} h/yr and 2.81×10^{-10} as shown in Table 7. Moreover, the overall benefit obtained in this case study is 1.83×10^5 $/yr, this indicates that significant cost savings have been accomplished with the integration of RERs and ESS.

The incorporation of the PV, WTG and ESS into a microgrid has contributed a substantial effect to the reduction of operating parameters such as LCC, COE, GEC_{total}, AC_{loss}^{load}, EENS, LOLE and LOLP. Having compared the six case studies based on some key performance indicators, it is well established that the case study 6 is the most economic, environmental and reliability feasible. This shows that the cost savings of a microgrid system can be enhanced with the integration of

Table 6
Environmental analysis of the case studies.

Case study	CO_2 (kg)	Nox (kg)	SO_2 (kg)	Reduced CO_2 (kg)	Reduced Nox (kg)	Reduced SO_2 (kg)
1	3.20×10^6	3.26×10^4	1.75×10^3	0	0	0
2	3.01×10^6	3.07×10^4	1.65×10^3	1.87×10^5	1.91×10^3	1.02×10^2
3	2.84×10^6	2.90×10^4	1.56×10^3	3.57×10^5	3.64×10^3	1.96×10^2
4	2.36×10^6	2.40×10^4	1.29×10^3	8.41×10^5	8.56×10^3	4.60×10^2
5	2.08×10^6	2.12×10^4	1.14×10^3	1.12×10^6	1.14×10^3	6.10×10^2
6	1.81×10^6	1.84×10^4	9.90×10^2	1.39×10^6	1.42×10^3	7.61×10^2

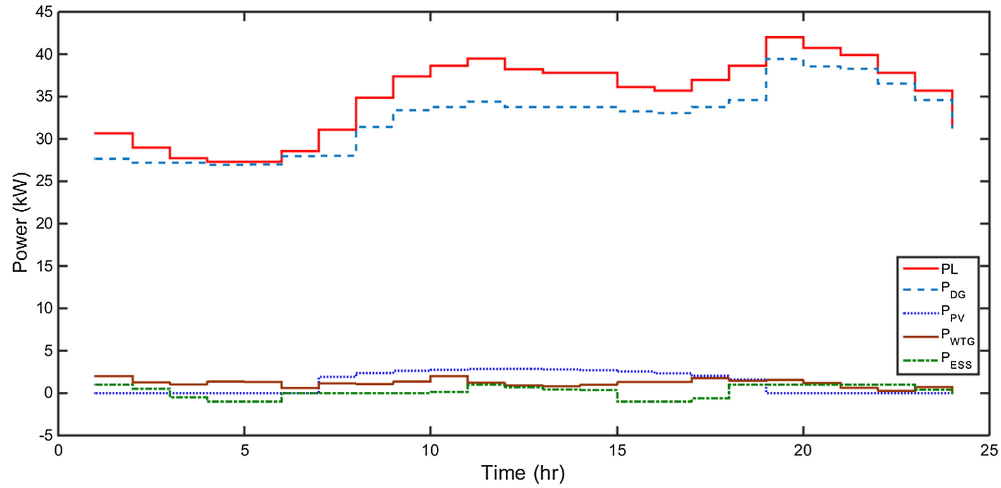

Fig. 6. Case study 2: variations of load demand, power from the diesel generator, PV, WTG and ESS.

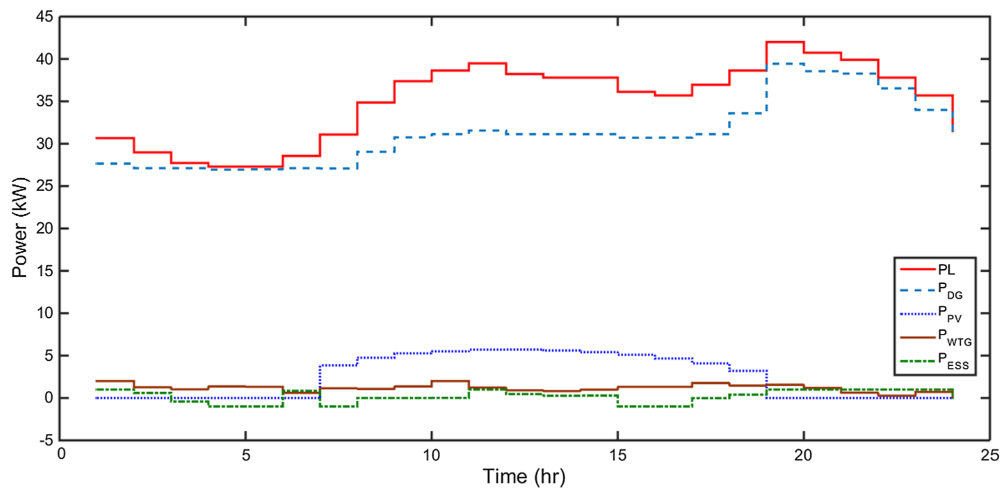

Fig. 7. Case study 3: variations of load demand, power from the diesel generator, PV, WTG and ESS.

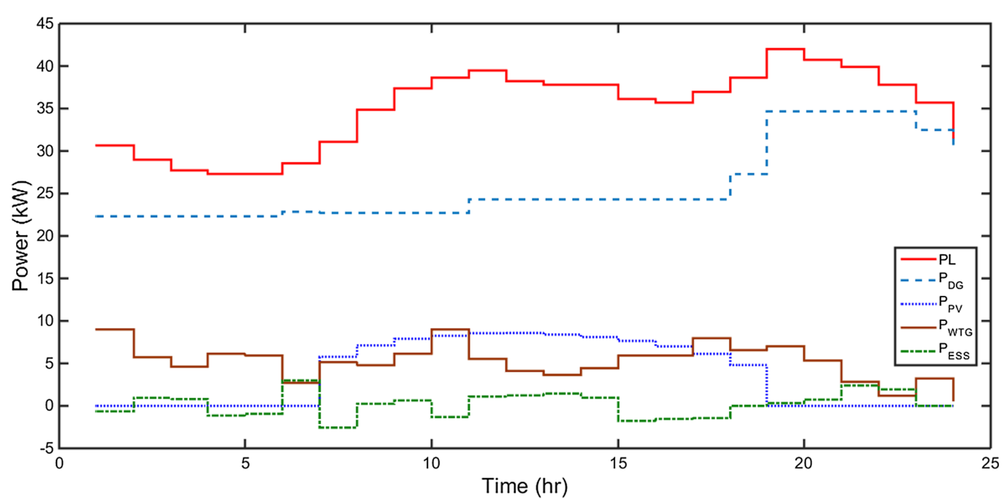

Fig. 8. Case study 4: variations of load demand, power from the diesel generator, PV, WTG and ESS.

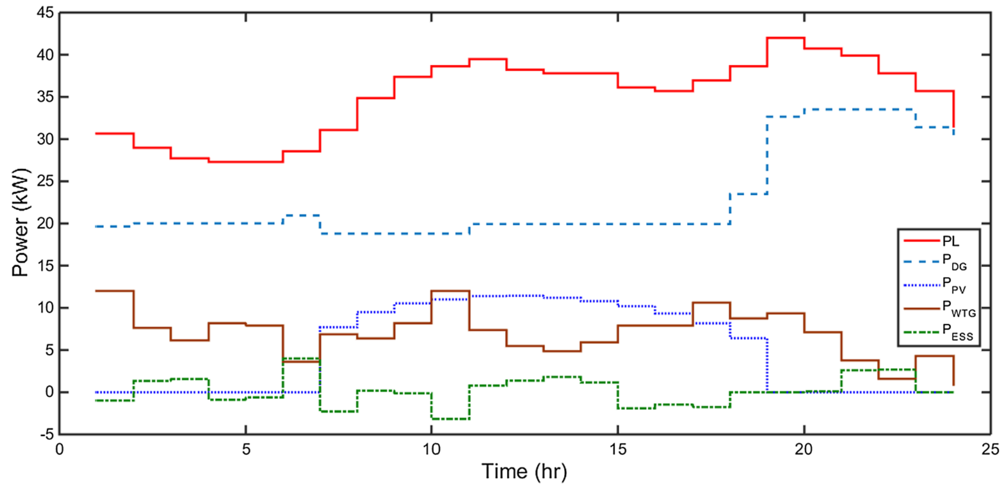

Fig. 9. Case study 5: variations of load demand, power from the diesel generator, PV, WTG and ESS.

the additional number of green technologies. It is also important to note that the benefits of RERs when compared with the brown technologies depend on the availability of the local RERs, the capacity of the battery and the level of renewable energy technologies penetration. These factors must be considered at the conceptual and design stages of a microgrid project that involves the incorporation of RERs.

8. Sensitivity analysis

In this research work, a sensitivity analysis is carried out to investigate the effects of fluctuations of diesel fuel price on the microgrid operation. A slight increase in the price of crude oil results in an increase in the COE and this reduces the revenues of the utilities. It has been noted on the global record that variations in the international crude oil price can result in a sudden change in the price of diesel fuel. This will invariably be transferred to the consumers in the form of high and unstable COE. Moreover, the impacts of unexpected changes in the costs of the major components that constitute the microgrid system such as PV, WTG and ESS units are also investigated. The incremental improvements in technology coupled with manufacturing design and inspection aided by information technology can reduce the prices of renewable energy technologies. Similarly, the influence of interest rates is one of the market factors considered in this work to investigate the economic operation of a microgrid system. In the theory of lifecycle economic analysis, the aforementioned market factors affect the optimal operation of a power system. In addition to this, the effects of forced outage rate, peak load variations and the PV, WTG and ESS penetration level on the reliability of a microgrid system are also investigated. Hence, the sensitivity analysis is carried out on case study 6 that has the best feasibility based on the reliability, economic and environmental benefits.

8.1. Effect of fuel price variations on the microgrid performance

In recent times, fossil fuel has been reported to be the largest contributor to universal primary energy consumption and one of the biggest drivers of the global economy. The uncertainty in the political atmosphere in oil producing countries is a vital instrument that causes wide variations in international fuel prices. Therefore, crude oil demand-supply dynamics critically influence the international price of crude oil. Whenever such fluctuations occur, many countries in the world are subject to many economic challenges. The effects of fuel price fluctuations on the performance of a microgrid are analyzed by varying the diesel fuel price from 3% to 18% while maintaining the costs of other components that constitute the system. It is observed in Figs. 11a and 11b that the COE and lifecycle cost are increasing while the overall benefit is decreasing with variation in the prices of diesel fuel. This result shows that the fluctuation in the prices of the diesel fossil fuel is very sensitive to the operation of the power system. Thus, it can affect the economic performance of a microgrid system. This indicates that changes in the price of diesel fuel should be considered as one of the cogent factors in the lifecycle economic analysis. The results prove that

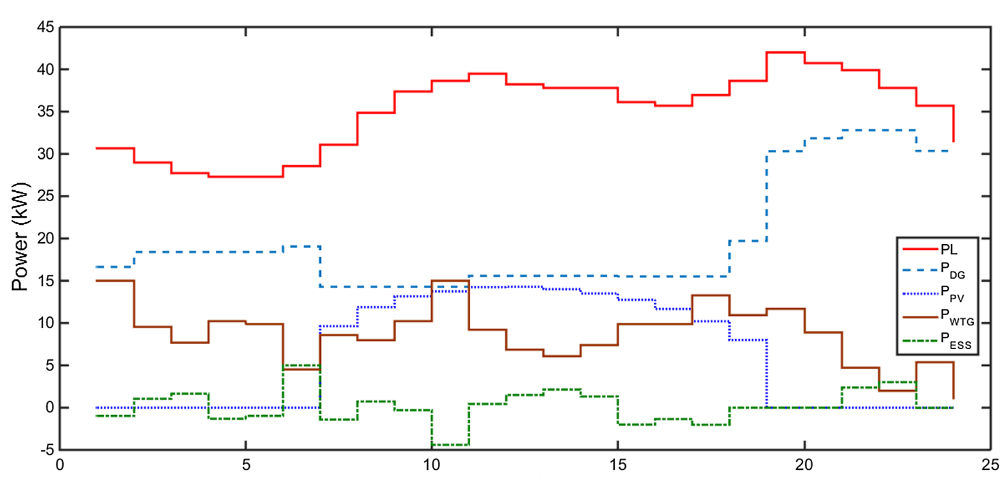

Fig. 10. Case study 6: variations of load demand, power from the diesel generator, PV, WTG and ESS.

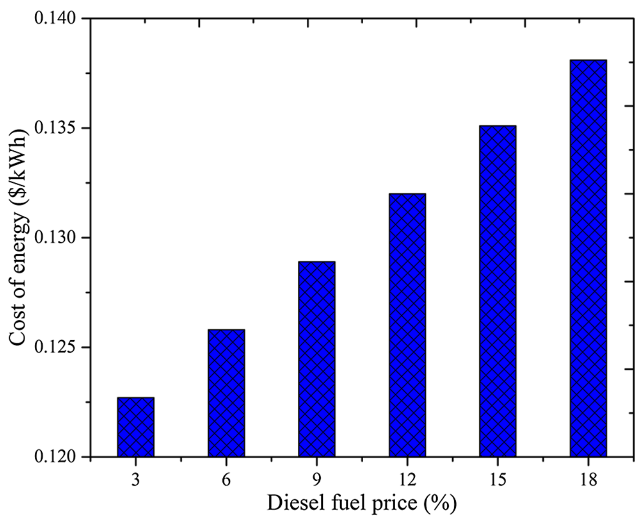

Fig. 11a. Effect of fuel price variations on the cost of energy.

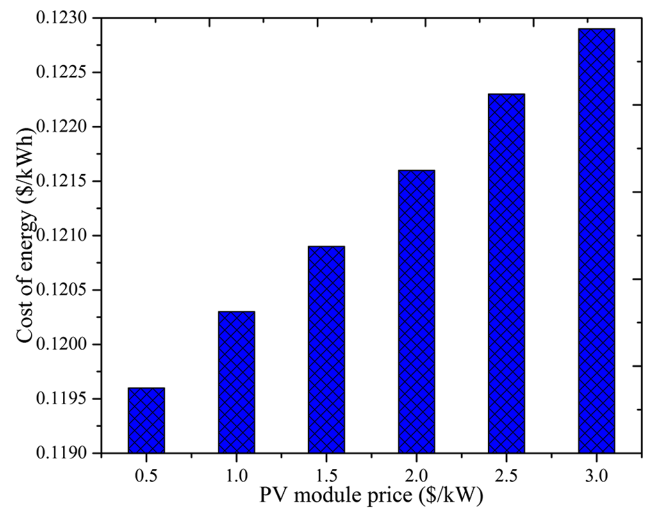

Fig. 12a. Effect of the PV price changes on the cost of energy.

the influence of diesel fuel price fluctuations is a prominent factor in the assessment of the optimal operation of a microgrid system.

8.2. Effect of capital cost on the economic performance of a microgrid system

In this subsection, the changes in the prices of the major components that constitute the proposed microgrid are studied and analyzed based on the LCC, COE and overall benefit while the price of the diesel fuel is maintained.

8.2.1. Sensitivity analysis of a microgrid with changes in the prices of the PV module

The analysis is carried out by changing the price of the PV module from 0.5 $/kW to 3 $/kW, while maintaining the prices of other components of the proposed microgrid system and the price of diesel fuel. The program was run to estimate the corresponding change of economic performance indicators in terms of COE, LCC and benefits. The results presented in Figs. 12a and 12b show that the values of COE and LCC increase while overall benefit decreases with an increase in the price of the PV module. This shows that the price of the PV module contributes a substantial percentage to the performance of a microgrid system. Therefore, a reduction in the price of the PV module through government incentives and improvement in technology will result in a decrease in the values of LCC and COE. Moreover, this will also increase the overall benefit of the PV module in the microgrid system since RERs are more favoured in terms of economic and environmental benefits when compared with the brown technologies.

8.2.2. Sensitivity analysis of a microgrid with changes in the prices of the WTG unit

Capital cost is one of the cogent factors that is considered in the sensitivity analysis of a microgrid system since unpredictability of the worldwide economy can cause a specific level of uncertainty in the economic performance of a power system. In view of this, the change in the price of the WTG unit is investigated in this case study while maintaining the prices of other components that constitute the system and the price of diesel fuel. The results obtained by changing the price of the WTG units from 0.5 $/kW to 3 $/kW show that the values of the COE and LCC are increasing while the overall benefit is decreasing with an increase in the price of the WTG unit as shown in Figs. 13a and 13b. The indicates that with the implementation of renewable energy sustainability policy and the recent trend in the technology, the price of the WTG units will eventually reduce. This will invariably reduce the values of COE and LCC and enhance the benefits of the WTG in the microgrid systems. The government must also introduce some initiatives in the form of subsidies and tax cuts to reduce the capital cost

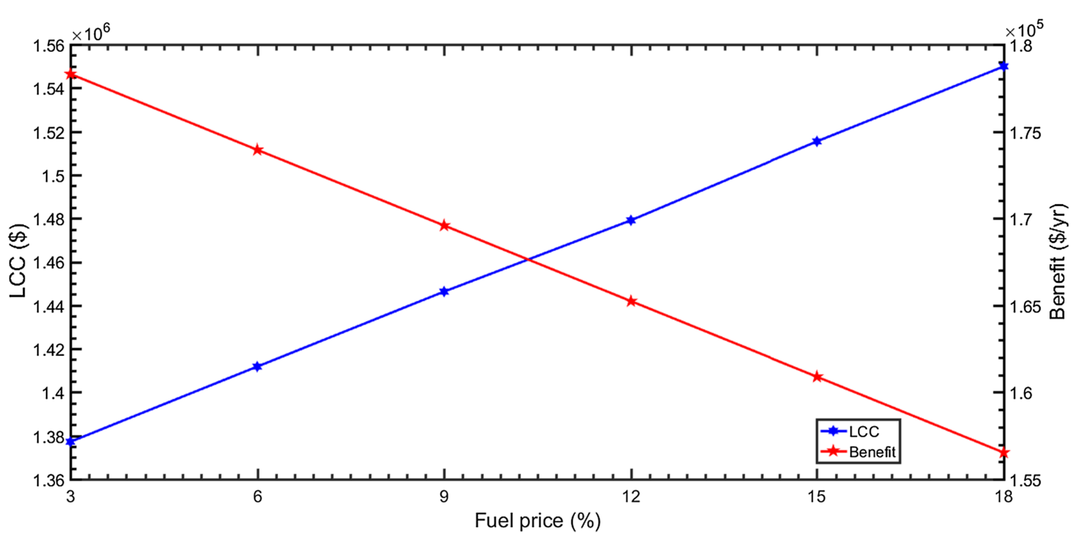

Fig. 11b. Effect of fuel price variations on the LCC and overall benefit.

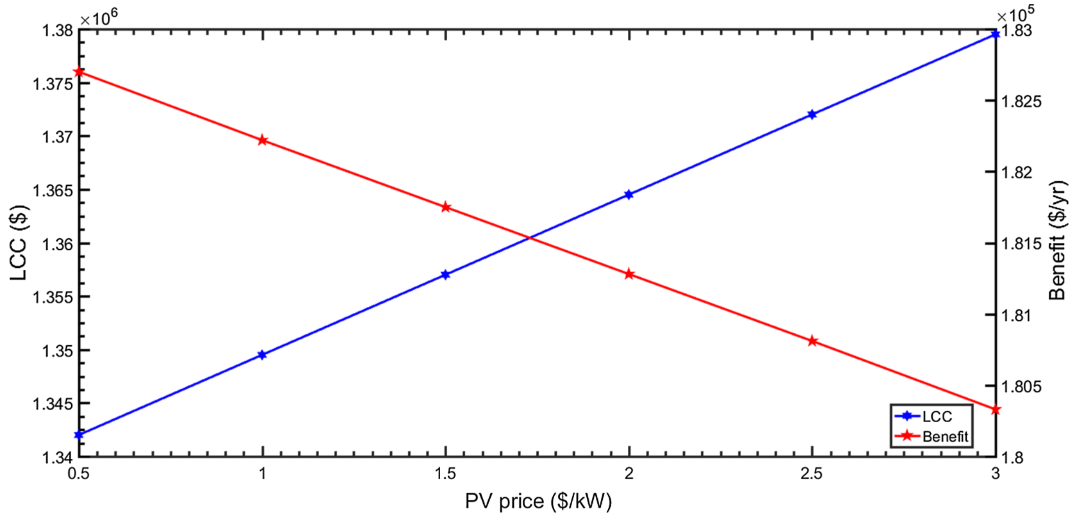

Fig. 12b. Effect of the PV price variations on the LCC and overall benefit.

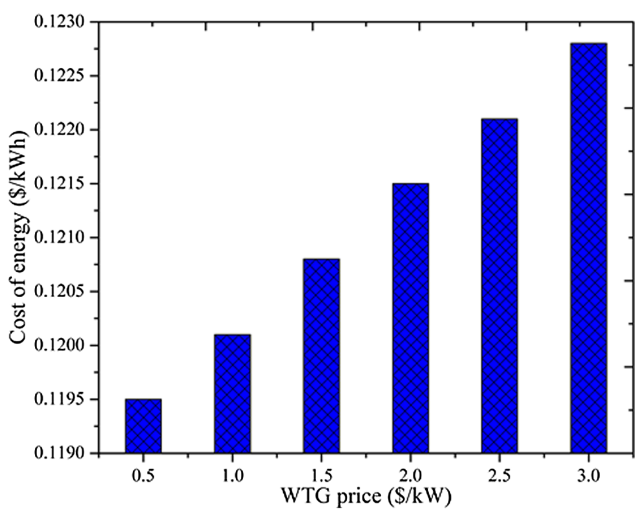

Fig. 13a. Effect of the WTG variations on the cost of energy.

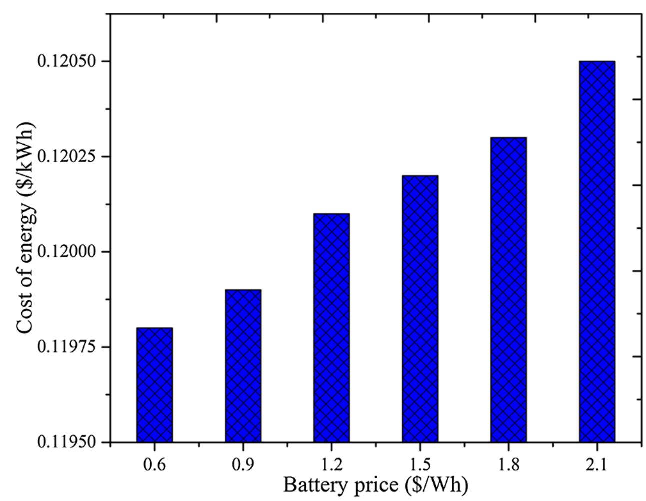

Fig. 14a. Effect of the ESS price variations on the cost of energy.

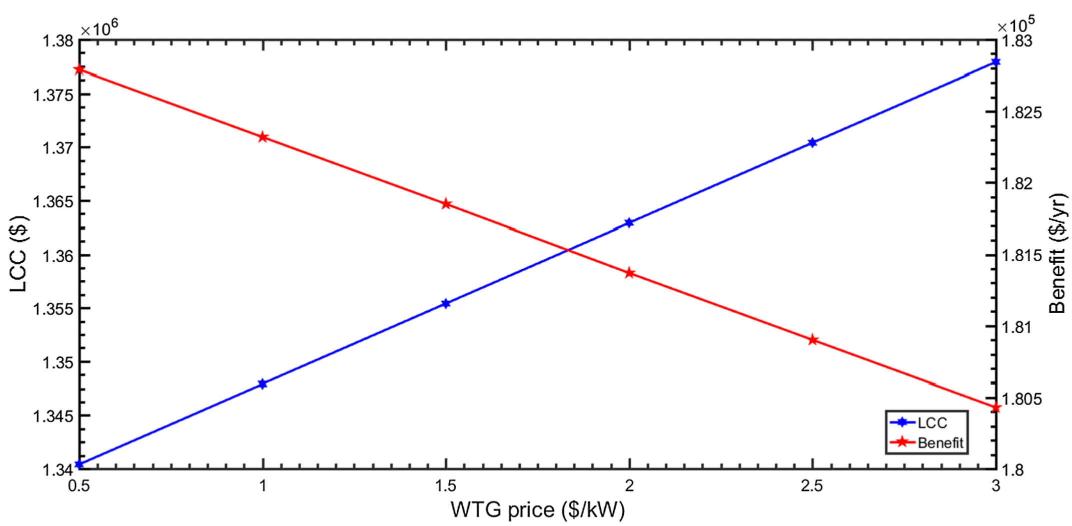

Fig. 13b. Effect of the WTG price variations on the LCC and overall benefit.

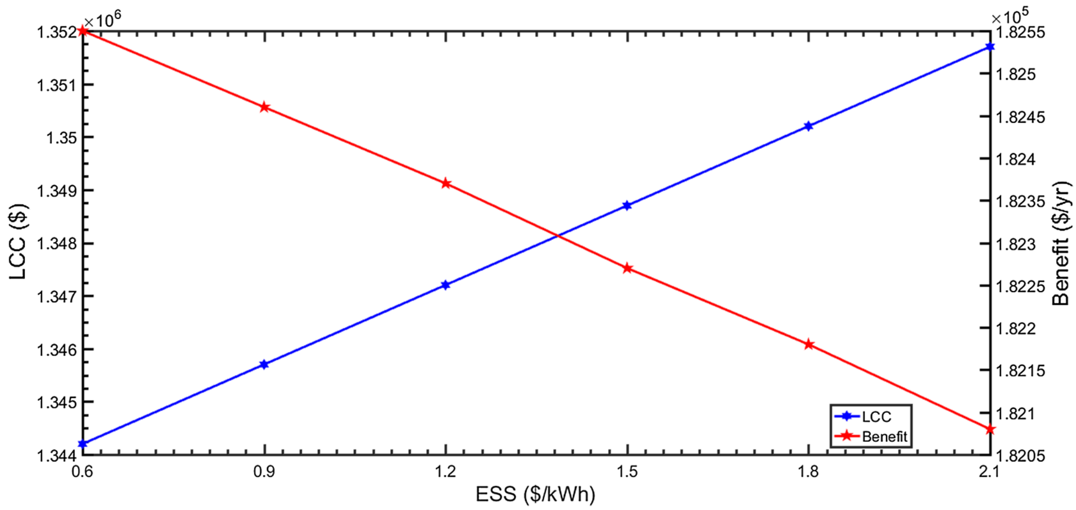

Fig. 14b. Effect of the ESS price variations on the LCC and overall benefit.

of the WTG units. These policies will encourage the utilization of local RERs in rural areas where access to electricity has become a serious issue.

8.2.3. Sensitivity analysis of a microgrid with changes in the prices of the electric storage system

The sensitivity analysis of a microgrid system based on changes in the prices of the ESS is presented in Figs. 14a and 14b. This shows that an increase in the price of the ESS increases the values of the LCC and COE and causes a decrease in the overall benefit of the system. This indicates that changes in the prices of the ESS influence the values of LCC, COE and overall benefit. If the prices of the ESS can be reduced with the tax holiday and government incentives, the values of LCC and COE will reduce and this will also improve the overall benefit of green technologies in a power system.

8.3. Effect of the interest rate on the economic performance of a microgrid system

The renewable energy sustainability requires a substantial investment in the procurement of green energy technologies to generate electricity based on their economic, environmental and technical benefits. Moreover, market factor such as interest rate plays a vital role in energy investment choice and decisions as well as the economic performance of a microgrid system. The interest rate affects the capital costs of the major components that constitute a power system and optimal operation of renewable energy technologies to compete with brown energy technologies. In view of this, we have investigated the impact of interest rates on the COE, LCC and overall benefit of a microgrid system. In this context, the ranges of interest rate and inflation rate selected are (8–16%) and (4–12%) in step of 2% respectively by using case study 6 as presented in Table 4. The effects of the interest rates as presented in Figs. 15a and 15b show that the COE, LCC and overall benefit react differently to changes in the interest rates. The values of the COE and LCC are directly proportional to the change in the value of the interest rate. This indicates that the values of the COE and LCC increase in proportion to the interest rates. On the other hand, the value of the overall benefit is decreasing as the interest rates are increasing. To improve the competitiveness of the green technologies with the brown technologies, some cogent steps must be put in place by the utilities and government. Hence, based on the analysis of the interest rates on the microgrid system, we come out with three significant conclusions:

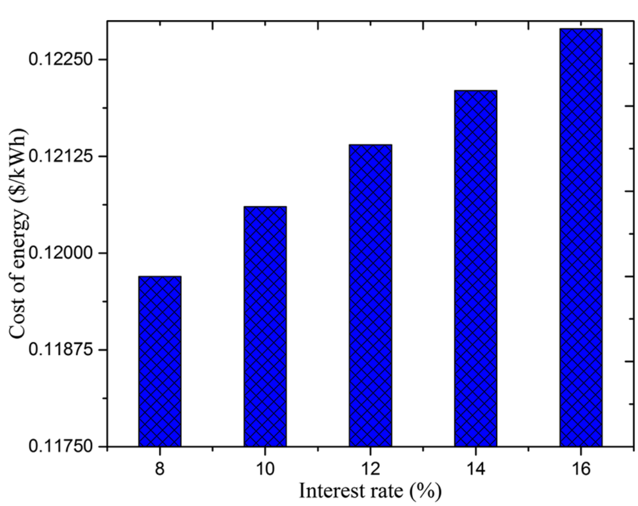

Fig. 15a. Effect of interest rate on the cost of energy.

- A low-interest-rate environment makes the operation of a PV/WTG/ESS/diesel generator microgrid system to be highly economical feasible.
- A microgrid system with the integration of the PV, WTG and ESS reacts significantly to a change in interest rates.
- In order to increase the economic performance of a microgrid system, we suggest a discount on the interest rates for the PV, WTG and ESS units. This makes the operation of a microgrid system to be more efficient.

8.4. The effect of peak load variations of the power system

The peak load and load profile of consumers are important factors that must be considered during the reliability assessment of a generating system. The reliability performance of a power system depends on the load variations and the annual peak load. The impacts of peak load variations in the power system are considered and investigated in this subsection by utilizing the reliability indices such as EENS, LOLE and LOLP. Case study 6 with the configuration presented in Table 4 is used in this study to investigate the impacts of peak load on the reliability of the power system. The peak load is varied from 42 kW to 60 kW and the values of the reliability indices are increasing according to the peak load variations. The results obtained by varying the peak load indicate that it has a significant effect on the reliability of a power system. It can be seen in Figs. 16a–16c that the power system risk is proportional to the variation of peak load. This indicates that the

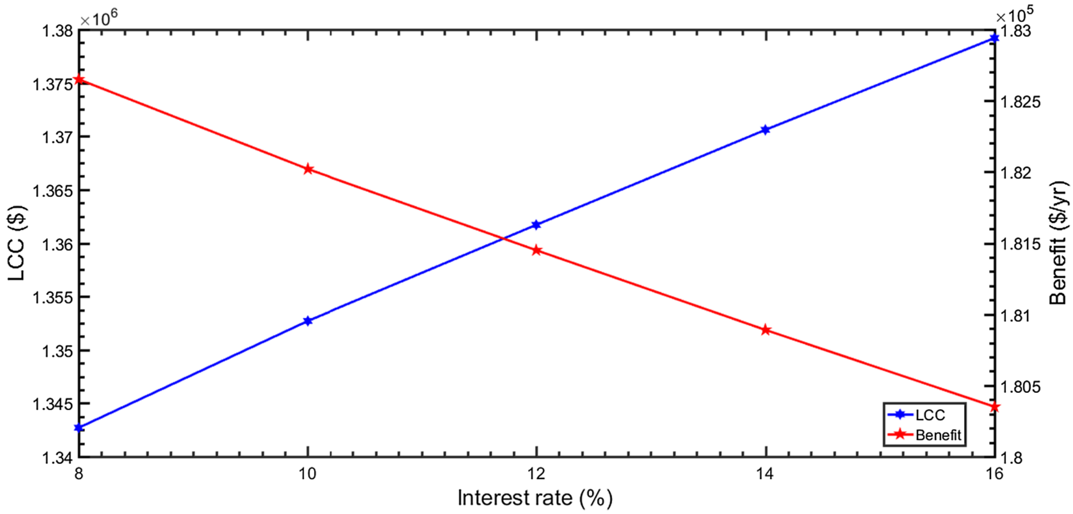

Fig. 15b. Effect of interest rate on the LCC and overall benefit.

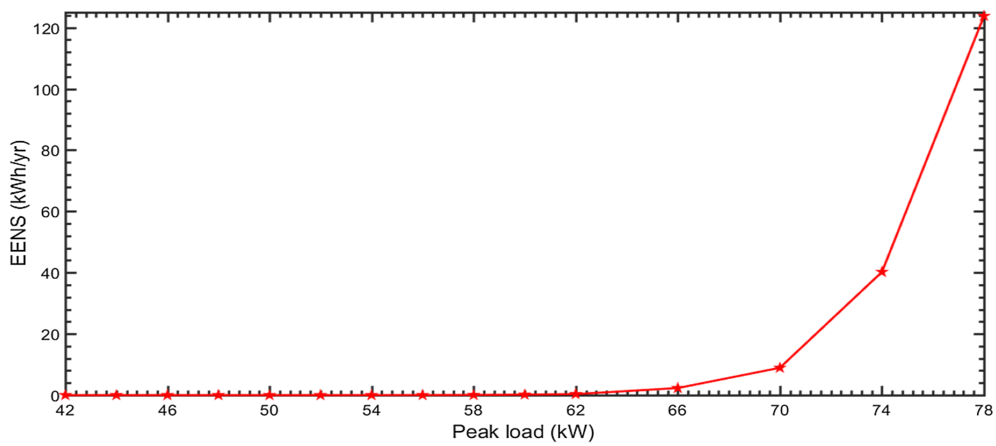

Fig. 16a. Effect of annual peak load on EENS.

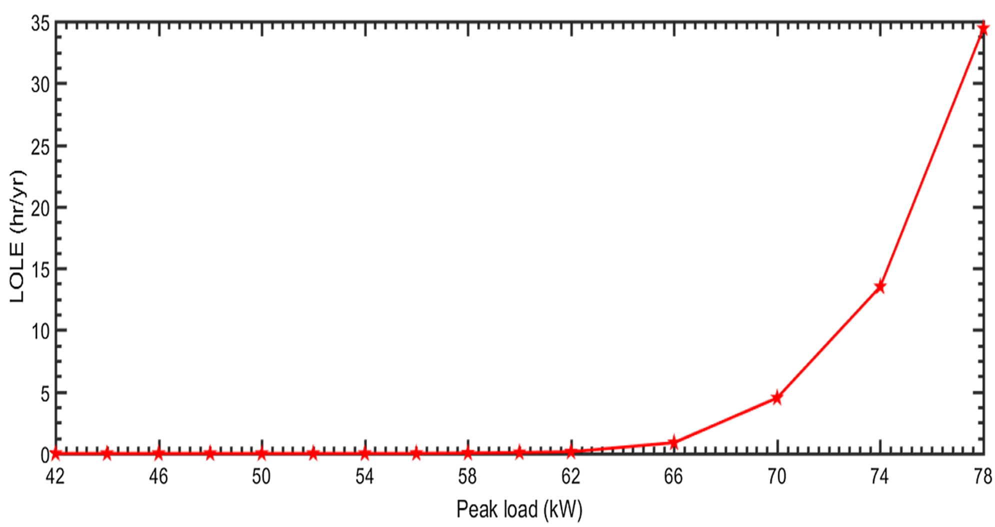

Fig. 16b. Effect of annual peak load on LOLE.

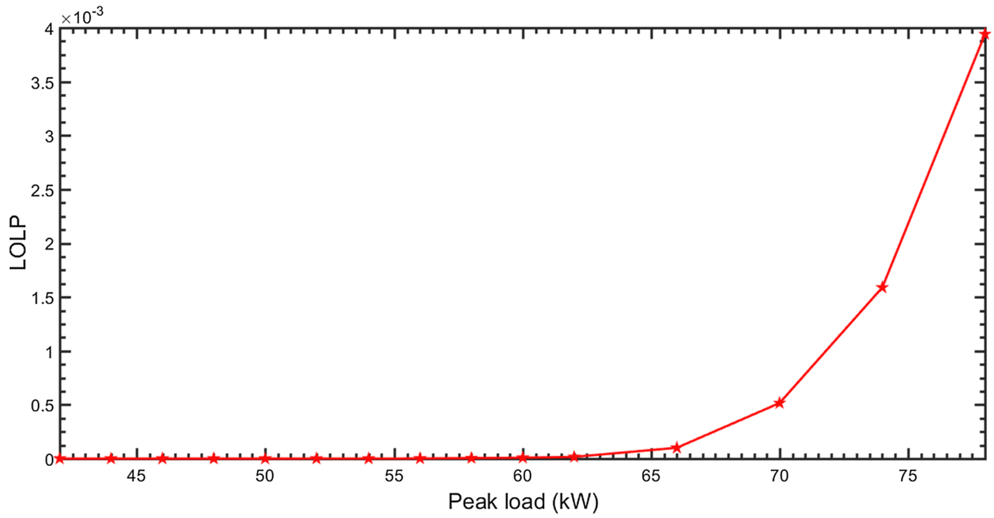

Fig. 16c. Effect of annual peak load on LOLP.

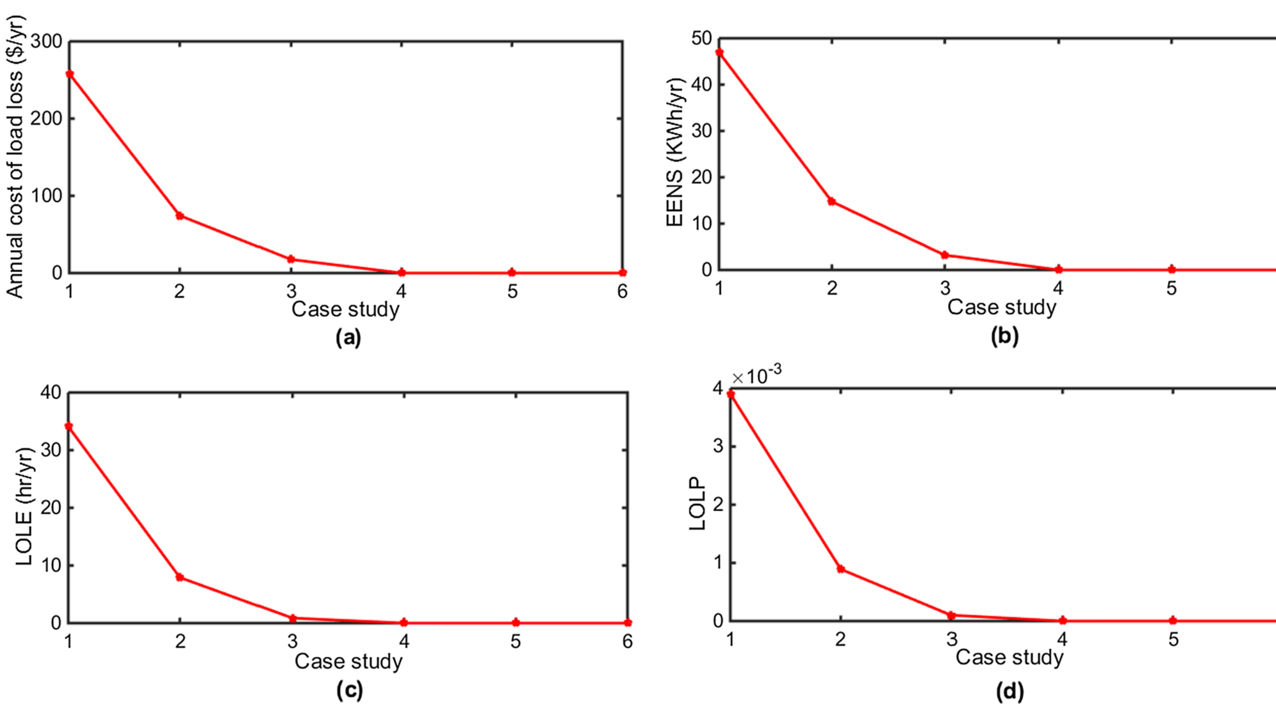

Fig. 17. Impacts of WTG, PV and ESS on (a) annual cost of load loss (b) EENS, (c) LOLE and (d) LOLP.

system is no more reliable by periodically increasing the peak load. The results depicted in Figs. 16a–16c show that the peak load has a significant impact on the power outages. For this reason, the power utilities must consider the load growth as one of the cogent factors to assess the present and future performance of the power system. The distribution network operators can meet the projected load growth by designing their power systems with a number of backup units in the form of distributed energy technologies. This will reduce the socio-economic risk that is associated with power interruptions.

8.5. The effect of the PV, WTG and ESS penetration

The adequacy of generation capacity is investigated in this subsection with the penetration of PV, WTG and ESS units. This is illustrated by adding different units of the PV, WTG and ESS to the case study 1 as shown in Table 4. The results presented in Fig. 17a–d depict the effects of the aforementioned units on the reliability indices of the system such as the annual cost of load loss, EENS, LOLE and LOLP. The aforementioned reliability indices are decreasing with the penetration of the additional number of PV, WTG and ESS units. This shows that the application of RERs improves the reliability of the proposed microgrid system. The values of the reliability indices recorded are due to the high penetration level of the PV, WTG and ESS. The excess power produced with the integration of additional RERs into the system can be used by consumers while the rest is stored in the battery bank. Furthermore, this has established the fact that any RER added to the base system will enhance the reliability of the system. It shows the significant impact RERs on the adequacy of the power system. The reliability of the system will continue to increase with the integration of RERs units, until when the improvement will be marginal after some level.

8.6. Effect of force outage rate on the reliabity of power system

The reliability of the power system is strongly affected by the forced

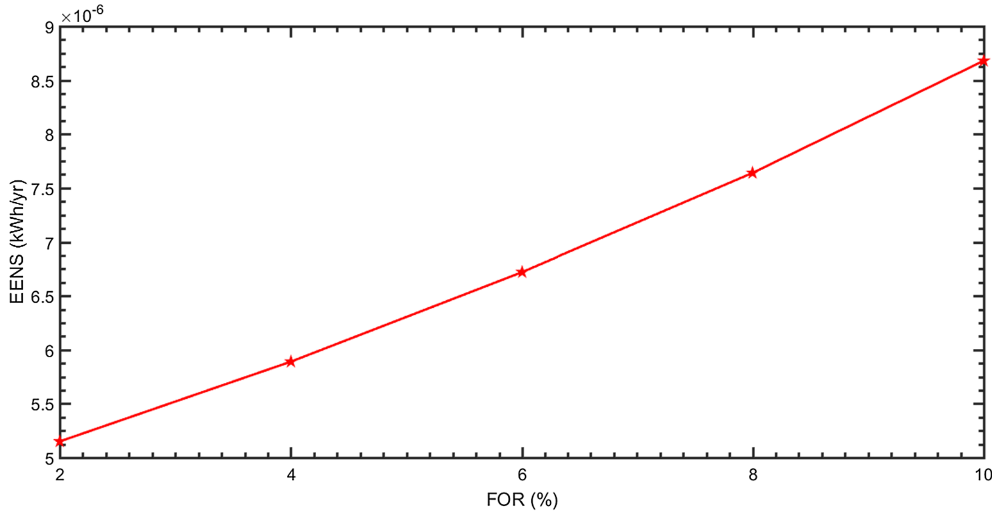

Fig. 18a. Effect of diesel generator force outage rate on EENS.

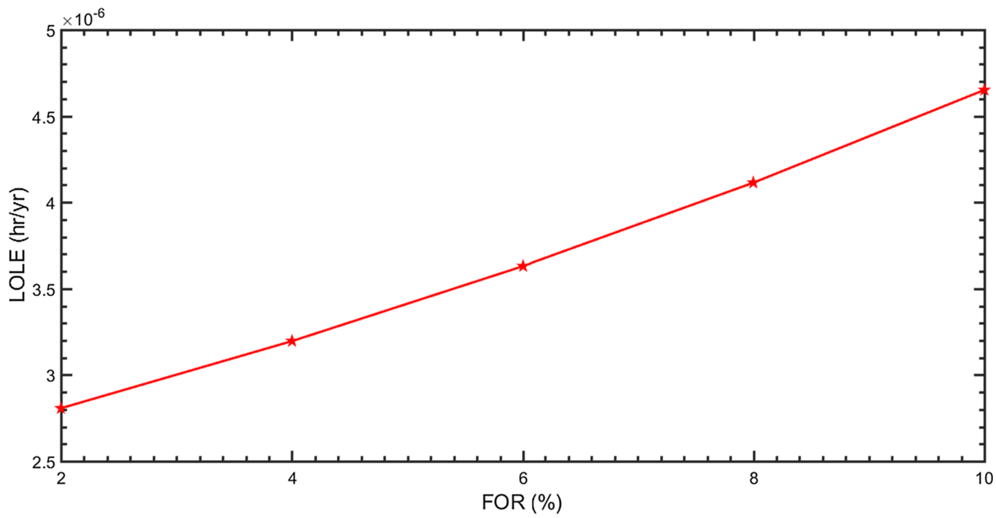

Fig. 18b. Effect of diesel generator force outage rate on LOLE.

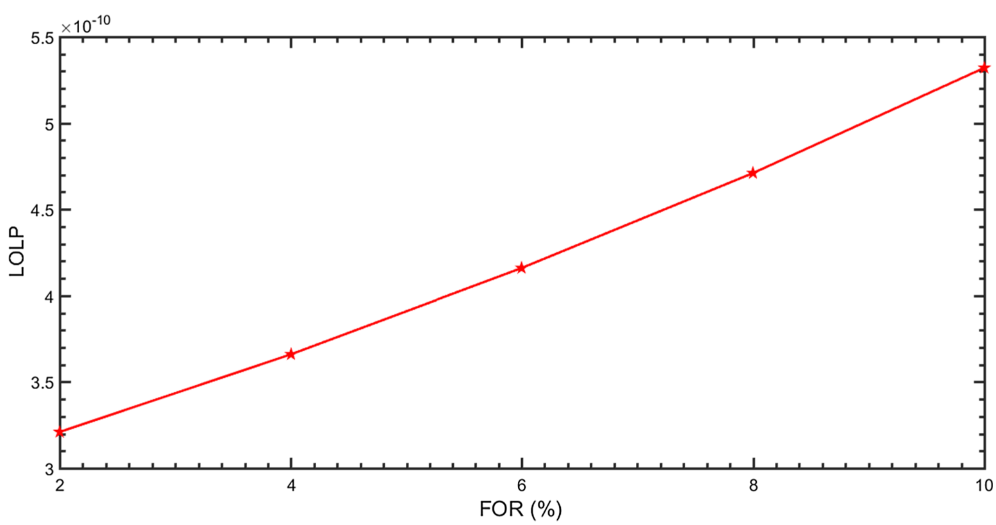

Fig. 18c. Effect of diesel generator force outage rate on LOLP.

outage rate of the generating units. In this subsection, the effects of FOR on a number of generating units are investigated on the adequacy of the power system. This is achieved by varying the values of FOR for the diesel generator, PV and WTG in case study 6 with the configuration presented in Table 4. To justify the effects of the forced outage rate in the power system, the values of FOR for the diesel generator, PV, WTG

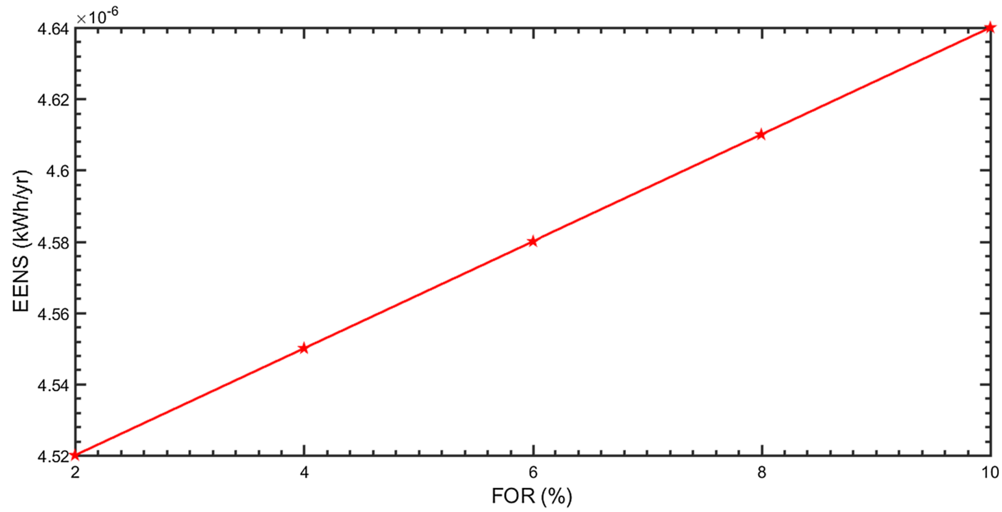

Fig. 19a. Effect of PV force outage rate on EENS.

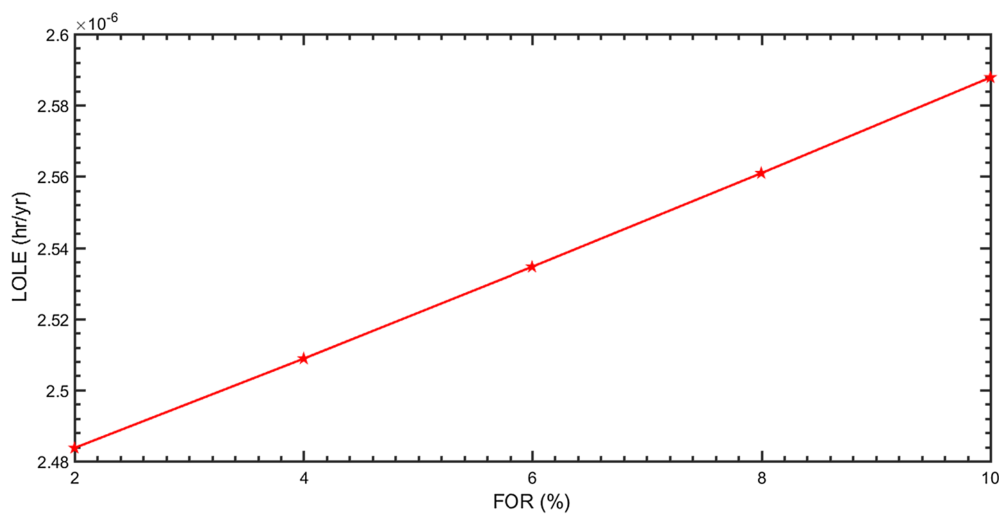

Fig. 19b. Effect of PV force outage rate on LOLE.

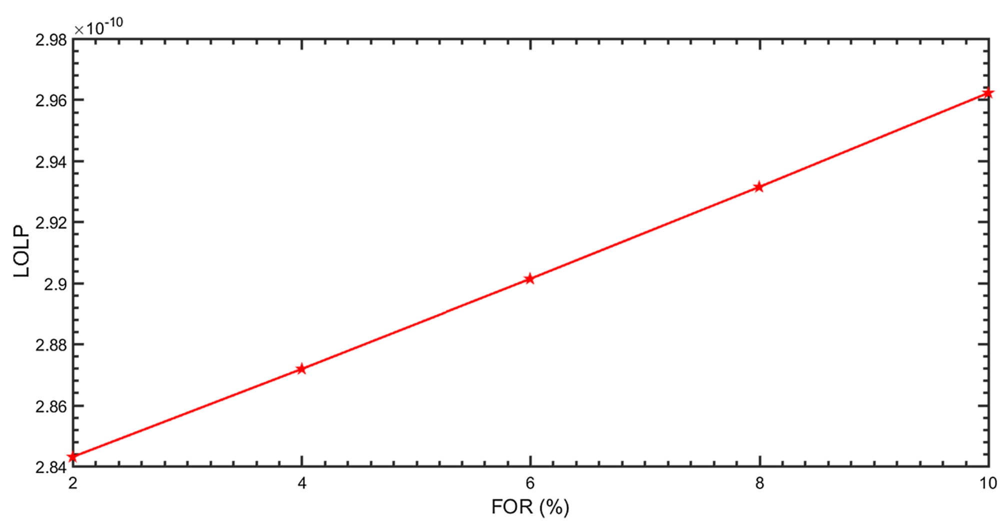

Fig. 19c. Effect of PV force outage rate on LOLP.

and ESS are varied from 2% to 10% with the steps of 2%. It is observed that the values of EENS, LOLE and LOLP increase slightly as the values of FOR of the diesel generator, PV and WTG increase. This indicates that the reliability performance of the power system is reduced with an increase in the values of FOR of the generating units as shown in Figs. 18–21. For this reason, the power utilities must strategize different

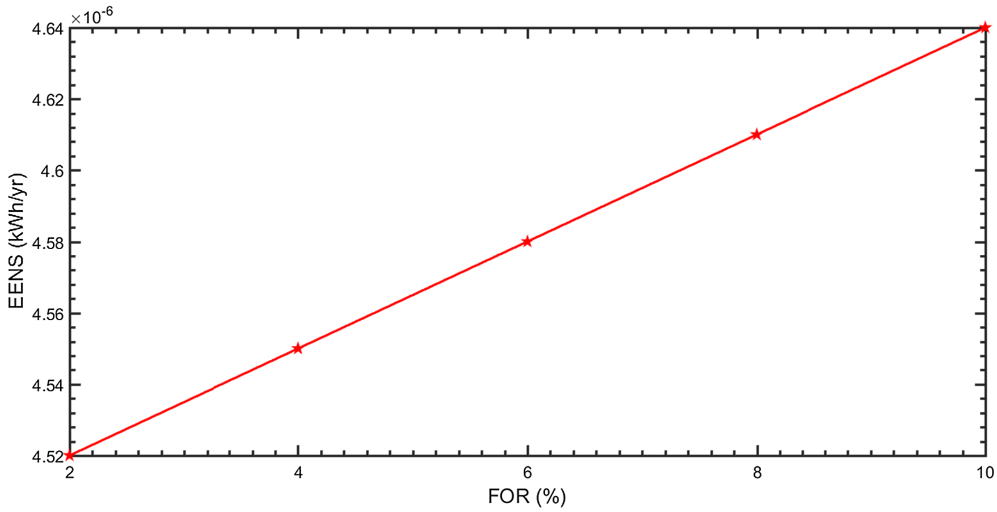

Fig. 20a. Effect of WTG forced outage rate on EENS.

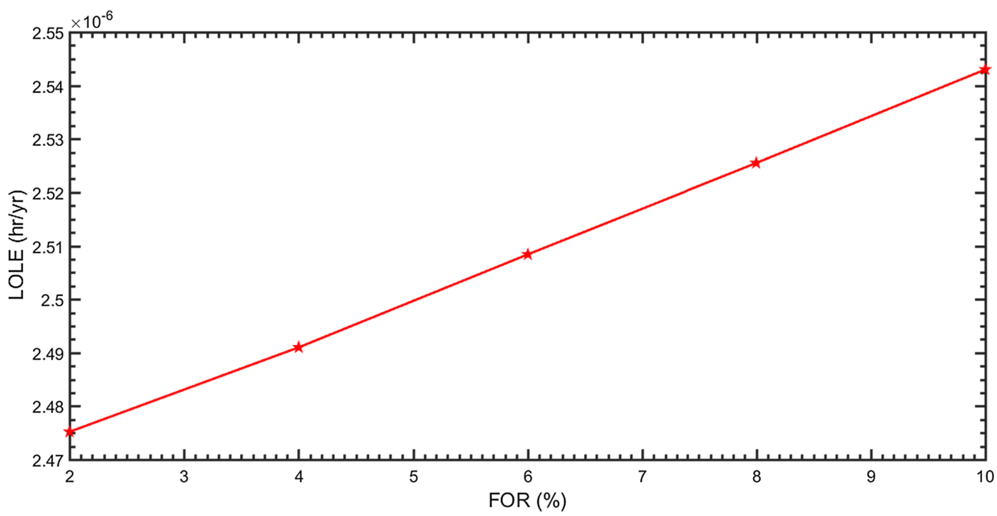

Fig. 20b. Effect of WTG forced outage rate on LOLE.

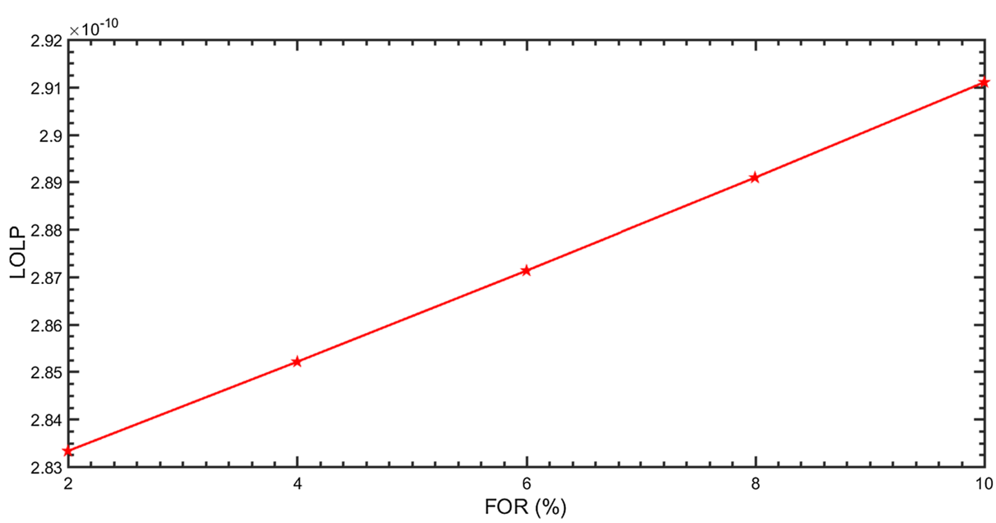

Fig. 20c. Effect of WTG forced outage rate on LOLP.

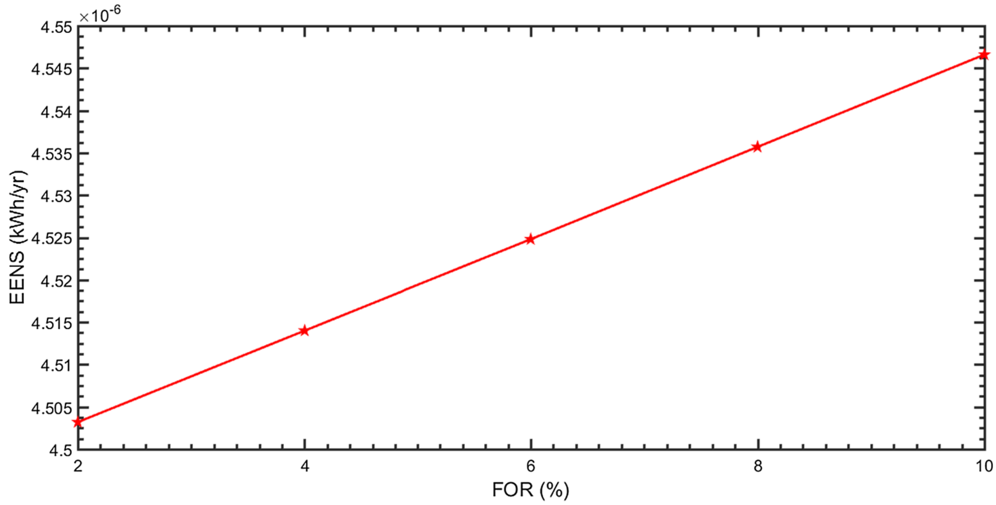

Fig. 21a. Effect of ESS forced outage rate on EENS.

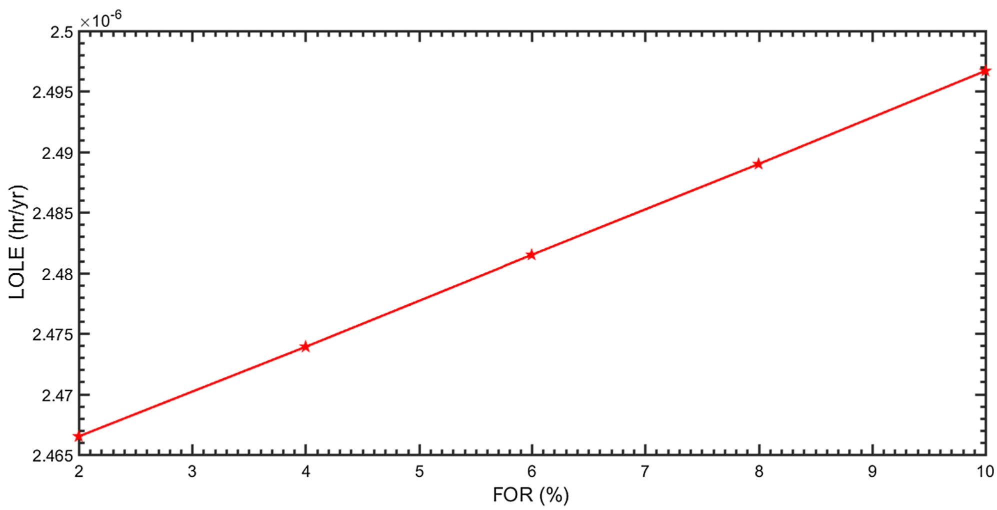

Fig. 21b. Effect of ESS forced outage rate on LOLE.

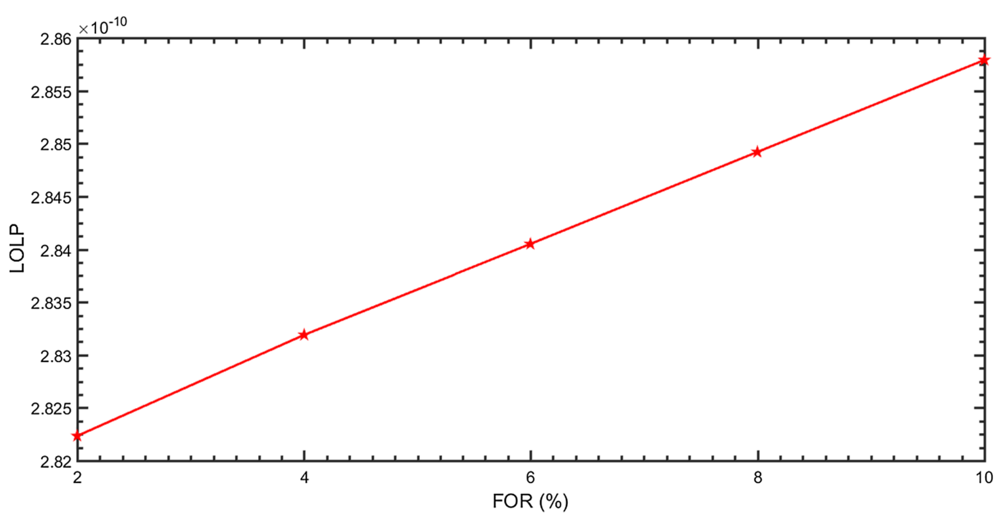

Fig. 21c. Effect of ESS forced outage rate on LOLP.

measures to improve the reliability of their power system by using a number of backup units such as WTG, PV and ESS and application of different maintenance schemes to reduce unscheduled outages due to the failure of the generating units. This will not only improve the performance of the system but also increase the profit margin of different organizations and reduce the economic risk that is related to power outages.

This work focuses on the development of the models for the evaluation of the impacts of RERs on the reliability, environmental and economic proficiency of a power system. Based on the unique features of some RERs, the models can be used by the utilities to accomplish the optimal operation of a power system. It has been established from the results of the simulation that the technique developed in this research work can be used in the analysis of real-time power system. Thus, this paper presents a more practical model that can be used in real time power applications. It can help the distribution network operators to understand the concept and benefits of RERs and economic analysis of a microgrid system. The multi-objective function adopted in this work can assist the power utilities and power system planners to make the optimal decisions when facing numerous objectives. The results, models and discussions presented in this research work have provided significant information to the utilities for appropriate planning and operation of their systems with the integration of RERs. The results obtained from this research work can be used to measure the effectiveness of investing in RERs to increase the capacity of the global power generation. This can resolve the power crisis that many countries are facing on the global note. The following information is achieved from results obtained in this study:

(i) The multi-objective functions that have the ability to accept numerous input are developed in this work.
(ii) The best solution is obtained in case study 6 owing to optimum reliability, economic and environmental benefits.
(iii) A microgrid configuration with the incorporation of renewable energy resources and electric storage system is technically and economically better than using the diesel generator only to meet the power demand in terms of the lifecycle cost, cost of energy, annual cost of load loss, greenhouse gas emission cost and overall benefit.
(iv) The results obtained from the sensitivity analysis show that the economic, environmental and reliability performances of the proposed microgrid system depend on:
- Fuel price fluctuations.
- Changes in the prices of photovoltaic, wind turbine generator and electric storage system.
- Changes in the interest rates.
- The level of photovoltaic, wind turbine generator and electric storage system penetration.
- Peak load variations.
- Forced outage rate.

9. Conclusion

The main objective of this study was to assess the impacts of photovoltaic, wind turbine generator and electric storage system on the microgrid system that has a 25-year time horizon. The optimization problem is based on multi-objective functions that involve the cost of energy, lifecycle cost, lifecycle greenhouse gas emission cost, annual cost of load loss and overall benefit. The aforementioned key operating indicators are employed in this study to validate the cost and technical effectiveness of utilizing green technologies in a microgrid system. This study is designed to assist the utilities for the financial planning of sustainable energy projects in the countries where access to electricity is limited owing to some financial and technical constraints. The methodology adopted in this research work can be used to measure the effectiveness of investing in renewable energy technologies to enhance the capacity of the global power generation. This should resolve the power crisis that many countries are facing currently. The concepts applied in this study will assist the power system designers, planners and managers to evaluate the economic, environmental and reliability benefits of using green technologies in the microgrid systems. The technique utilized in this work can also be used to solve many socio-economic problems that are related to the engineering design of a microgrid and provides significant information for making managerial decisions. The results obtained from this work show that the number of people without access to electricity can be reduced significantly with the application of renewable distributed energy resources, coupled with improvements in technologies and decline in the costs of microgrid components. The key performance indicators utilized in this paper are recommended for energy regulatory agencies when compiling information for annual electricity market reports and activities of the utilities on the security of power supply.

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References

[1] Al Mamun K, Amanullah MTO. Smart energy grid design for island countries. Springer; 2018.
[2] Roy A, Kabir MA. Relative life cycle economic analysis of stand-alone solar PV and fossil fuel powered systems in Bangladesh with regard to load demand and market controlling factors. Renew Sustain Energy Rev 2012;16(7):4629–37.
[3] International Energy Agency. World energy outlook 2017 – executive summary; 2017. Available: https://www.iea.org/access2017/ [accessed November, 2018].
[4] Adefarati T, Bansal RC. Reliability and economic assessment of a microgrid power system with the integration of renewable energy resources. Appl Energy 2017;206:911–33.
[5] Adefarati T, Bansal RC, Justo JJ. Reliability and economic evaluation of a microgrid power system. Energy Procedia 2017;142:43–8.
[6] Catalão JP. Smart and sustainable power systems: operations, planning, and economics of insular electricity grids. CRC Press; 2017.
[7] Adefarati T, Bansal RC. Integration of renewable distributed generators into the distribution system: a review. IET Renew Power Gener 2016;10(7):873–84.
[8] Adefarati T, Bansal RC. Reliability assessment of distribution system with the integration of renewable distributed generation. Appl Energy 2017;185:158–71.
[9] Adefarati T, Bansal RC. The impacts of PV-wind-diesel-electric storage hybrid system on the reliability of a power system. Energy Procedia 2017;105:616–21.
[10] Gampa SR, Das D. Optimum placement and sizing of DGs considering average hourly variations of load. Int J Electr Power Energy Syst 2015;66:25–40.
[11] Li M, Lin Z, Ji T, Wu Q. Risk constrained stochastic economic dispatch considering dependence of multiple wind farms using pair-copula. Appl Energy 2018;226:967–78.
[12] Malheiro A, Castro PM, Lima RM, Estanqueiro A. Integrated sizing and scheduling of wind/PV/diesel/battery isolated systems. Renew Energy 2015;83:646–57.
[13] Das BK, Al-Abdeli YM, Kothapalli G. Optimisation of stand-alone hybrid energy systems supplemented by combustion-based prime movers. Appl Energy 2017;196:18–33.
[14] Dufo-López R, Bernal-Agustín JL, Yusta-Loyo JM, Domínguez-Navarro JA, Ramírez-Rosado IJ, Lujano J, et al. Multi-objective optimization minimizing cost and life cycle emissions of stand-alone PV–wind–diesel systems with batteries storage. Appl Energy 2011;88(11):4033–41.
[15] Singh S, Singh M, Kaushik SC. Feasibility study of an islanded microgrid in rural area consisting of PV, wind, biomass and battery energy storage system. Energy Convers Manage 2016;128:178–90.
[16] Ma T, Yang H, Lu L. A feasibility study of a stand-alone hybrid solar–wind–battery system for a remote island. Appl Energy 2014;121:149–58.
[17] Zhao B, Zhang X, Li P, Wang K, Xue M, Wang C. Optimal sizing, operating strategy and operational experience of a stand-alone microgrid on Dongfushan Island. Appl Energy 2014;113:1656–66.
[18] Brodrick PG, Brandt AR, Durlofsky LJ. Optimal design and operation of integrated solar combined cycles under emissions intensity constraints. Appl Energy 2018;226:979–90.
[19] Ogunjuyigbe A, Ayodele T, Akinola O. Optimal allocation and sizing of PV/Wind/Split-diesel/Battery hybrid energy system for minimizing life cycle cost, carbon emission and dump energy of remote residential building. Appl Energy 2016;171:153–71.
[20] Bortolini M, Gamberi M, Graziani A, Pilati F. Economic and environmental bi-objective design of an off-grid photovoltaic–battery–diesel generator hybrid energy system. Energy Convers Manage 2015;106:1024–38.
[21] Chade D, Miklis T, Dvorak D. Feasibility study of wind-to-hydrogen system for Arctic remote locations–Grimsey island case study. Renew Energy 2015;76:204–11.
[22] Azimoh CL, Klintenberg P, Mbohwa C, Wallin F. Replicability and scalability of mini-grid solution to rural electrification programs in sub-Saharan Africa. Renew Energy 2017;106:222–31.
[23] Amrollahi MH, Bathaee SMT. Techno-economic optimization of hybrid photovoltaic/wind generation together with energy storage system in a stand-alone micro-grid subjected to demand response. Appl Energy 2017;202:66–77.
[24] Shahzad MK, Zahid A, ur Rashid T, Rehan MA, Ali M, Ahmad M. Techno-economic feasibility analysis of a solar-biomass off grid system for the electrification of remote rural areas in Pakistan using HOMER software. Renew Energy

2017;106:264–73.
[25] Ghorbani N, Kasaeian A, Toopshekan A, Bahrami L, Maghami A. Optimizing a hybrid wind-PV-battery system using GA-PSO and MOPSO for reducing cost and increasing reliability. Energy 2018;154:581–91.
[26] Amutha WM, Rajini V. Cost benefit and technical analysis of rural electrification alternatives in southern India using HOMER. Renew Sustain Energy Rev 2016;62:236–46.
[27] González A, Riba J-R, Rius A, Puig R. Optimal sizing of a hybrid grid-connected photovoltaic and wind power system. Appl Energy 2015;154:752–62.
[28] Aghajani G, Shayanfar H, Shayeghi H. Demand side management in a smart micro-grid in the presence of renewable generation and demand response. Energy 2017;126:622–37.
[29] Ghazvini MAF, Soares J, Abrishambaf O, Castro R, Vale Z. Demand response implementation in smart households. Energy Build 2017;143:129–48.
[30] Nan S, Zhou M, Li G. Optimal residential community demand response scheduling in smart grid. Appl Energy 2018;210:1280–9.
[31] Bahmani-Firouzi B, Azizipanah-Abarghooee R. Optimal sizing of battery energy storage for micro-grid operation management using a new improved bat algorithm. Int J Electr Power Energy Syst 2014;56:42–54.
[32] Mohammadi M, Hosseinian S, Gharehpetian G. GA-based optimal sizing of micro-grid and DG units under pool and hybrid electricity markets. Int J Electr Power Energy Syst 2012;35(1):83–92.
[33] Maleki A, Pourfayaz F. Optimal sizing of autonomous hybrid photovoltaic/wind/battery power system with LPSP technology by using evolutionary algorithms. Sol Energy 2015;115:471–83.
[34] Dufo-López R, Cristóbal-Monreal IR, Yusta JM. Optimisation of PV-wind-diesel-battery stand-alone systems to minimise cost and maximise human development index and job creation. Renew Energy 2016;94:280–93.
[35] Abbes D, Martinez A, Champenois G. Life cycle cost, embodied energy and loss of power supply probability for the optimal design of hybrid power systems. Math Comput Simul 2014;98:46–62.
[36] Shi Z, Wang R, Zhang T. Multi-objective optimal design of hybrid renewable energy systems using preference-inspired coevolutionary approach. Sol Energy 2015;118:96–106.
[37] Sanajaoba S, Fernandez E. Maiden application of Cuckoo Search algorithm for optimal sizing of a remote hybrid renewable energy System. Renew Energy 2016;96:1–10.
[38] Nadjemi O, Nacer T, Hamidat A, Salhi H. Optimal hybrid PV/wind energy system sizing: application of cuckoo search algorithm for Algerian dairy farms. Renew Sustain Energy Rev 2017;70:1352–65.
[39] Morano P, Tajani F, Locurcio M. GIS application and econometric analysis for the verification of the financial feasibility of roof-top wind turbines in the city of Bari (Italy). Renew Sustain Energy Rev 2017;70:999–1010.
[40] Kamjoo A, Maheri A, Dizqah AM, Putrus GA. Multi-objective design under uncertainties of hybrid renewable energy system using NSGA-II and chance constrained programming. Int J Electr Power Energy Syst 2016;74:187–94.
[41] Das CK, Bass O, Kothapalli G, Mahmoud TS, Habibi D. Optimal placement of distributed energy storage systems in distribution networks using artificial bee colony algorithm. Appl Energy 2018;232:212–28.
[42] van der Stelt S, AlSkaif T, van Sark W. Techno-economic analysis of household and community energy storage for residential prosumers with smart appliances. Appl Energy 2018;209:266–76.
[43] Parra D, Norman SA, Walker GS, Gillott M. Optimum community energy storage for renewable energy and demand load management. Appl Energy 2017;200:358–69.
[44] Li Y, Feng B, Li G, Qi J, Zhao D, Mu Y. Optimal distributed generation planning in active distribution networks considering integration of energy storage. Appl Energy 2018;210:1073–81.
[45] Parra D, Gillott M, Norman SA, Walker GS. Optimum community energy storage system for PV energy time-shift. Appl Energy 2015;137:576–87.
[46] Marini A, Latify MA, Ghazizadeh MS, Salemnia A. Long-term chronological load modeling in power system studies with energy storage systems. Appl Energy 2015;156:436–48.
[47] Sardi J, Mithulananthan N, Gallagher M, Hung DQ. Multiple community energy storage planning in distribution networks using a cost-benefit analysis. Appl Energy 2017;190:453–63.
[48] Santos SF, Fitiwi DZ, Cruz MR, Cabrita CM, Catalão JP. Impacts of optimal energy storage deployment and network reconfiguration on renewable integration level in distribution systems. Appl Energy 2017;185:44–55.
[49] Adefarati T, Bansal RC, Justo JJ. Techno-economic analysis of a PV–wind–battery–diesel standalone power system in a remote area. J Eng 2017;2017(13):740–4.
[50] Karampelas P, Ekonomou L. Electricity distribution. Springer; 2016.
[51] Generator set ISO 8528 power ratings explained. Available: http://www.fgwilson.ie/files/generator-set-iso-8528-power-ratings-explained.pdf [accessed: November, 2018].
[52] Adefarati T, Papy NB, Thopil M, Tazvinga H. Non-renewable distributed generation technologies: a review. In: Handbook of distributed generation. Springer; 2017. p. 69–105.
[53] Tazvinga H, Thopil M, Numbi PB, Adefarati T. Distributed renewable energy technologies. In: Handbook of distributed generation. Springer; 2017. p. 3–67.
[54] Del Granado PC, Pang Z, Wallace SW. Synergy of smart grids and hybrid distributed generation on the value of energy storage. Appl Energy 2016;170:476–88.
[55] Belfkira R, Zhang L, Barakat G. Optimal sizing study of hybrid wind/PV/diesel power generation unit. Sol Energy 2011;85(1):100–10.
[56] Wu Z, Xia X. Optimal switching renewable energy system for demand side management. Sol Energy 2015;114:278–88.
[57] Huang D. Basic considerations in electrical generating capacity adequacy evaluation. MSc. Thesis, Saskatoon Citeseer: University of Saskatchewan; 2005.
[58] Čepin M. Assessment of power system reliability: methods and applications. Springer Science & Business Media; 2011.
[59] Chauhan A, Saini R. A review on integrated renewable energy system based power generation for stand-alone applications: configurations, storage options, sizing methodologies and control. Renew Sustain Energy Rev 2014;38:99–120.
[60] Ardakani FJ, Riahy G, Abedi M. Design of an optimum hybrid renewable energy system considering reliability indices. In: 18th IEEE Iranian Conference on Electrical Engineering (ICEE); 2010. p. 842–47.