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Analysis and optimisation of a diesel-PV-wind-electric storage system for a standalone power solution

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Temitope Adefarati[1], Ramesh C. Bansal[2] ✉, Raj Naidoo[3], S. Potgieter[3], R. Rizzo[4], Padmanaban Sanjeevikumar[5]

[1]*Department of Electrical and Electronic Engineering, Federal University Oye Ekiti, Ekiti Sate, Nigeria*
[2]*Department of Electrical Engineering, University of Sharjah, Sharjah, United Arab Emirates*
[3]*Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria, South Africa*
[4]*Dipartimento di Ingegneria Elettrica e Tecnologie dell'Informazione, Università di Napoli Federico II Via Claudio, 21–80125 Napoli, Italy*
[5]*Department of Energy Technology, Faculty of Engineering and Science, Aalborg University Esbjerg, 6700 Esbjerg, Denmark*
✉ *E-mail: rcbansal@ieee.org*

Abstract: The universal power demand is increasing every day because of population growth, industrial revolution and high standards of living. The renewable energy technologies (RETs) are environmental and cost-effective solutions to satisfy dynamic load profile based on the application of multiple components of a standalone microgrid system that encompasses photovoltaic (PV), diesel generator (DG), electric storage system and wind turbine generator (WTG). This study reveals more insight into various research questions that have not been completely addressed in past investigations. The contributions of the study are expressed: (i) analyse the effects of RETs on the total cost, (ii) test the total benefits, (iii) estimate the market benefit share of the unit that reflects the benefit of one generation unit in proportion to the whole power system, (iv) maximise and minimise the yearly average power generated by (PV and WTG) and DG. This research work presents the application of fmincon optimising tool to accomplish the objectives of the study owing to some significant characteristics. The outcomes of the work show the validity of the model and can assist the utilities to minimise the costs that are identified with the optimal operation of their power systems.

1 Introduction

The sudden escalation in the universal energy demand is attributed to the modernisation of energy technologies, digitalisation of industrial sector, abrupt growth in domestic power consumption, population growth and economic growth [1]. Based on this assumption, the UNDP sustainable energy development goal is designed to increase access to a clean energy and reduce 84% of people that are currently living without access to the power supply in remote areas. Microgrid system is a potential option to increase affordable power supply in remote communities where grid connection is not economically viable. The proliferation of the traditional power system with several microgrid systems is to provide affordable and reliable electricity service to customers. As the interest for power generation is impressively expanded, energy mix that comprises sustainable and has expected fossil fuels is an alternative solution to decrease over-dependence on petroleum products. Owing to the negative effects of fossil fuel on soil degradation and ecosystems, it is imperative to emphasise the importance of green energy technologies in sustainable energy development goal. This will allow the preservation of ecosystem that has been endangered with the operation of conventional power plants, while providing the sustainable energy demand that cities require.

The utilisation of fossil fuels with their environmental effects has made the microgrid operators (MGOs) to deliberate on renewable energy technologies (RETs) as the viable choice to tackle the issues that are identified with the operation of the conventional power stations [2]. The sudden growth in the gross domestic product of many countries has triggered the congestion of transmission and distribution (T&D) infrastructures, the only viable solution in certain nations is to upgrade the existing T&D lines or integrate RETs into the existing traditional power system with the smart grid features [3]. The upgrading of the existing power infrastructure under power demand is a tedious task that requires a magnanimous budgetary allocation and technical proficiency. This has prompted the public that have no access to electricity to proliferate the standalone power systems with multiple RETs [4]. The microgrid systems are planned and designed by the power utilities in certain areas to operate as either grid-connected power system or off-grid power system or both [5]. This shows that in a circumstance where the power utility failed to meet the load demand, the concerned customers can automatically or manually change their operating mode from one status to another [6].

The proliferation of the traditional power system with various green energy technologies that operate without greenhouse gas (GHG) emission is globally believed to solve the problem of environmental pollution and climate change. The joint operation of the PV and WTG system is an acceptable option when compared with the fossil-based power plants owing to the availability of non-replenish solar and wind resources and no GHG pollutant when being used [7]. This has placed the use of RETs in a significant place to improve the global access to electricity.

The application of renewable power generation can be effectively and efficiently utilised in the microgrid systems owing to some significant technical and economic benefits. This shows that RETs have contributed a significant framework to green energy generation portfolio by taking appropriate management measures and considering operating characteristics of each component of a power system. The utilisation of RETs has considerably obtained global attention because of the simplicity of incorporating them into the microgrid systems [8]. The green energy technologies are flexible power sources the MGOs can use to supply electrical power to remote areas at a minimised operation and maintenance costs. This is because of how RETs can be used in off-grid in the absence of fossil fuels and can operate effectively with no connection to the utility grid. Also, it is very expensive to connect some rural areas to the utility grid owing to the economy of scale; some remote communities are sparsely populated, physical terrains and rivers. It can save a great deal of money with the utilisation of RETs-based microgrid systems.

In recent times, several techniques have been applied to study the effects of RETs on performance of the power systems. Several researchers have used key performance indicators (KPIs); this shows to test the importance of green energy technologies for rural electrification projects. Das *et al.* [9] have presented genetic algorithm (GA) on the cost of energy (COE), CO_2 emission and waste heat of a standalone hybrid energy system that encompasses PV, battery system (BS), diesel generator (DG) and gas turbines. In another study, Cristóbal-Monreal and Dufo-López [10] have investigated the effects of RETs on a microgrid system that comprises BS, DG and PV by using GA. The aim of the study is achieved by considering the monthly ambient temperature and averaged solar irradiation. Kim *et al.* [11] have presented an optimal scheme for BS by considering the reliability and economy of a microgrid system. The state of charge (SOC) of the BS is taken into consideration while investigating the effect of BS on the reliability of a power system without capturing the attenuation effect of the state of health of the BS. Liu *et al.* [12] have assessed the reliability of the power system by taking into consideration the attenuation of state of health and various components of BS. Cicilio *et al.* [13] have presented uGrid toolset for design and planning of mini-grid and resource allocation performance and sizing optimisation of energy generation infrastructure based on statistical load estimates. Li *et al.* [14] have proposed energy management and sizing technique method for a standalone system that encompasses PV, fuel cell and BS. The aim of the work was achieved by using the mixed-integer linear programming and GA based on constraints such as grid power, hydrogen storage power, PV power generated, BS power and load demand at time *t*. Yan and co-workers [15] have implemented the feasibility analysis of a grid-connected PV, hydrogen and BS by utilising peak shaving strategy, conventional strategy and hybrid operation strategy. Zhao *et al.* [16] have proposed a method for sizing the significant components of a standalone system such as PV, WTGs, ESS and DG. The multi-objective function took into consideration the following KPIs: emissions, costs and renewable energy generation. Nojavan *et al.* [17] have presented the loss of load expectation by using a Monte Carlo technique to determine the reliability performance of the distribution system. Ogunjuyigbe *et al.* [18] have carried out economic and environmental analyses of hybrid resources by using several scenarios and optimisation method.

The evaluation of a microgrid system has been implemented by using many KPIs, optimisers in MATLAB toolbox and techniques. This shows that a few studies have presented the importance of the microgrid systems in remote areas. Most of the sustainable energy development works reviewed in this work are dominated by costs to determine the optimal solutions for power system management. The objective functions of the aforementioned reviewed papers considered the combinations of COE, emissions, waste heat and reliability indices. None of the above research work has applied total benefits, total cost and yearly average power generation as the objective function simultaneously. Besides this, most of the aforementioned research work does not estimate the market benefit share (MBS) and uses multiple power sources to minimise the total cost that is identified with the optimal operation of power systems and optimisation of MBS and yearly average power generation. To the best of the knowledge of the authors, nobody has performed the sustainable energy plan to optimise the objective function presented in this paper. It is needed for such a holistic approach to test the overall benefits of RETs in a microgrid system and to satisfy dynamic load demands and reduce energy consumption from a DG. As a measure to enhance the performance and effectiveness of the power system, the aim functions proposed in the study considered the technical, economic and environmental indicators such as emissions, fuel cost, maintenance cost, MBS and average power generation.

It has carried the optimisation of the standalone power systems out by utilising many techniques. This research paper presents the utilisation of the fmincon optimised in MATLAB toolbox to accomplish the objectives of the study owing to its unique characteristics, such as simple to implement, requires less computational time and has been widely used in several optimisation functions. The technique applied in the study is used to optimise the total cost of the system, total benefits and yearly average power generation of PV, WTG and DG. The application of MBS in the vertically integrated power system will allow the independent power providers (IPPs) to compete among themselves and maximise their profits by strategically use energy mixture. This will permit their power systems to be operating optimally and at the same to increase the annual revenue. However, if the power-generating units are not strategically located owing to some reasons, this will make the power system operation not to reach the optimal point.

This study allows the power sharing among the components of the power system as a basis to maximise the financial advantages of green energy technology. This study reveals more insight into various research questions that have not been completely answered in past works. The results obtained from the study establish the validity of the model and the positive effects of RETs on the power system optimal operations. The proposed technique can support the MGOs to minimise the costs that are related to the optimal operations of their power systems. The outcomes of the study show that the power solution from the proposed microgrid system will be a better solution for the rural electrification program. The results obtained from the study provide vital information that will allow the energy policymakers to make a moral decision while facing many solutions. The significant contributions of the study include:

i. The multi-objective function presented in the study is utilised to assess the economic and environmental effects of RETs on the operation of a microgrid system.
ii. Development of a model in which it can accomplish the improvement in sustainability of power supply with the utilisation of RETs.
iii. Analyse the effects of RETs on the total cost that comprises GHG emissions, fuel costs, maintenance costs and capital costs and calculate overall benefits of utilising RETs in a microgrid system.
iv. Presentation of a model that estimates the MBS of the unit *i* that reflects the benefit of one generation unit in proportion to the entire power system.
v. Development of a model that maximises the yearly average power generated by PV and WTG and minimises the yearly average power generation of DG
vi. Investigate the effects of using multiple power sources versus a single DG based on their operational characteristics.
vii. Introduction of a model that will help the distribution network operators to test the costs that are identified with the operations of their power systems.

The rest of the paper is organised as follows. Section 2 presents the basic concept of a microgrid system with its basic components. The problem formulation is presented in Section 3. Section 4 is focused on the economic assessment of a microgrid system. Section 5 is focused on the environmental evaluation of the power system. The design parameters of the proposed microgrid system and their specifications are presented in Section 6. In Section 7, the model presented in the study is used in the proposed microgrid system and implemented the simulation with the application of some case studies. The outcomes of the study are presented in Section 8. Finally, the conclusion that summarised the entire study and contributions of the work to the power system development are presented in Section 9.

2 Microgrid system

A microgrid system is a localised power system that comprises BS, green energy technologies, loads, energy management system, communication facilities and definable boundaries. It is a small-scale power system that can operate independently or collaboratively with the utility grids. It is a power system that is designed by the MGOs to operate with a local control capability that breaks off from the utility grid and operates autonomously in island mode as the economic conditions dictate using distributed

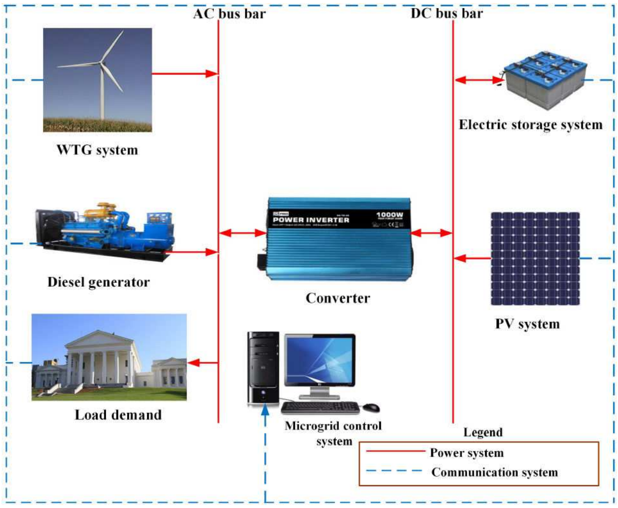

Fig. 1 *Schematic representation of a microgrid system with the power flow direction of its essential components*

generation during the crisis period like lightening, storm, scheduled and unscheduled power outages, trees, earthquakes, animals and excavation digging. It has the following benefits: it defers the costs that are related to the extension of T&D infrastructures to rural areas, lower COE and operation and maintenance cost, it can supplement the power supply from the utility grid during the peak period, makes the utility grid less susceptible to localised disaster, environmentally friendly, can meet the power requirement of essential loads during the emergency period and allows many communities to be more energy independent. The fundamental components of a microgrid system are briefly discussed in this section.

2.1 Photovoltaic (PV) system

The PV system comprises one or multiple number of solar panels and other hardware to convert solar energy to electricity. The size of the PV varies from small-scale rooftop mounted PV to medium-scale and large-scale PV plants. The PV system can be used for rural electrification and to supply electricity to the large commercial centres. The power output of the PV depends on the following parameters: solar radiation, surface area of the PV, temperature, the efficiency of the selected PV panel and location of the place where the PV is installed. They express the power generated by the PV system as [19]

$$P_{\rm pv} = \eta_{\rm pv} \times A_{\rm pv} \times I_{\rm pv} \tag{1}$$

where $I_{\rm pv}$ is the solar irradiation (kWh/m^2), $P_{\rm pv}$ is the power produced by the PV system (kW), $A_{\rm pv}$ is the surface area of the PV system (m^2) and $\eta_{\rm pv}$ is the efficiency of the PV system (%).

2.2 Wind turbine generator (WTG)

WTG is a device that converts the wind energy that exists at a site to electrical energy using the aerodynamic force from the WTG's rotor blades [15–18]. It is a clean energy source and cost-effective device that provides domestic, commercial and industrial power solution. It can be used in pursuing development of a sustainable energy goal. The selection of the WTG for a particular application depends on the meteorological data of the site where the WTG is installed, required power output and load demand [20]. The power output of the WTG is a function of air density, wind speed, rotor blade radius, location of the site and so on [19, 21, 22]. The WTG can be installed in a large open space based on the size of its rotor diameter. Of thumb, the distance between one WTG to another should be four times of the rotor diameter as a measure to prevent unnecessary interference between the WTG and a reduction in the power generated. This has made the installation of the WTG in the urban centres to be economically impracticable. Therefore, the remote areas with the spare population density and the favourable wind regime are ideal locations for the installation of the WTG. The power output of the WTG is presented as [23–27]

$$P_{\rm wind} = \frac{1}{2}\rho A v^3 C_p \eta_g \eta_b \tag{2}$$

where $P_{\rm wind}$ is the power produced by the WTG system (kW), ρ is the air density (kg/m^3), A is the turbine rotor swept area (m^2), v is the wind speed (mg/s), C_p is the coefficient performance, η_g is the generator efficiency (%) and η_b is the gear/bearing efficiency (%).

2.3 Electric storage system (ESS)

ESS encompasses one or more electrochemical cells that store chemical energy and latter convert it to electrical energy at the time of use. This shows that the ESS is purposely integrated into the microgrid systems by the MGOs to store the excess energy and release the stored energy into the power system during the peak period. ESS is a cost-effective device that is widely used in the microgrid systems for several functions such as backup, voltage regulation, frequency regulation, smoothing out the power output of RETs, peak shaving, emergency power supply and one of the critical components for optimisation of the power system [22, 23]. It uses technological techniques to provide sustainable energy for several consumers at the load points. The ESS is classified into: electrical, super capacitor, chemical, heat storage technologies, gravitational pressure and flywheel. The cost plays a substantial role while planning and designing a microgrid system, hence, a cheap ESS may be the most financially viable but not the most efficient. The operating limits of the ESS are presented as [19]

$$\left\{ {\rm SOC}^{\min} \le {\rm SOC}(o) + \eta_c \sum_{t=1}^{k} P_{\rm ess}^{c}(t) - \eta_d \sum_{t=1}^{k} P_{\rm ess}^{d}(t) \le {\rm SOC}^{\max} \right\} \tag{3}$$

where η_c is charge efficiency of the ESS (%), η_d is discharge efficiency of the ESS (%), $P_{\rm ess}^{d}$ and $P_{\rm ess}^{c}$ are the power and discharge and accepted by the ESS, ${\rm SOC}^{\max}$ is maximum SOC and ${\rm SOC}^{\min}$ is minimum SOC

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

3 Problem formulation

The first element of the objective function is formulated to minimize the TCS subject to the satisfaction of power system constraints and load requirements. The second element of the aim function is introduced to maximise the total benefits of using RETs in a microgrid system, the third and fourth elements of the objective function are to maximise the yearly average PV and WTG power generation from solar and wind resources, the fifth element of the objective function is to minimise the yearly average power generation from the DG. It presents the proposed microgrid system with its essential components, and the power flow direction in Fig. 1.

It presents the objective function coupled with the constraints of the proposed power system:

$$f = \min \sum_{i=1}^{n} \begin{pmatrix} f_{{\rm obj1},i} - f_{{\rm obj2},i} - f_{{\rm obj3},i} \\ - f_{{\rm obj4},i} + f_{{\rm obj5},i} \end{pmatrix} \tag{5}$$

where $f_{{\rm obj1},i}$, $f_{{\rm obj2},i}$, $f_{{\rm obj3},i}$ $f_{{\rm obj4},i}$ and $f_{{\rm obj5},i}$ are the first, second, third, fourth and fifth elements of the objective function.

The first element of the objective function to reduce the TCS of the power system is introduced as

$$f_{{\rm obj1},i} = \left(C_{\rm capital} + C_{\rm repl} + C_{\rm fuel} + C_{\rm emission} + C_m\right) \tag{6}$$

where C_{fuel} is the fuel cost, C_{repl} is the replacement cost, C_{capital} is the capital cost, C_{emission} is the emission cost and C_m is the maintenance cost.

The second element of the objective function to maximise the total benefits when compared with the base contextual investigation is applied. It uses some significant performance factors such as maintenance cost, emission cost, fuel cost and electricity cost. It summarises the expected benefits of incorporating RETs into the power system. This objective can be accomplished by comparing the economic values of the aforementioned KPIs with the based case study having considered the power generated by each unit.

The total benefit is expressed as

$$\sum_{i=1}^{4} \text{TB}_i = \sum_{i=1}^{4} \begin{pmatrix} \text{MC}_{\text{benefit},i} + \text{EC}_{\text{benefit},i} \\ +\text{FC}_{\text{benefit},i} + \text{EL}_{\text{benefit},i} \end{pmatrix} \quad (7)$$

$$f_{\text{obj2},i} = \sum_{i=1}^{4} TB_i \quad (8)$$

where $\text{MC}_{\text{benefit},i}$ is the maintenance cost, $\text{EC}_{\text{benefit},i}$ is the emission cost, $\text{FC}_{\text{benefit},i}$ is the fuel cost, $\text{EL}_{\text{benefit},i}$ is the electricity cost benefit and TB_i is the total benefit from electricity revenue, maintenance cost, fuel cost and emission cost when compared with the base case study, respectively.

The benefits presented in (8) can further be explained: the electricity benefit got from selling power to the load points when compared with a circumstance where DG is utilised alone to satisfy the power requirement. The electricity benefit is expressed as

$$\text{EC}_{\text{benefit},i} = \left\{ \sum_{i=1}^{n} P_{\text{gen},i} \times \text{COE}_{\text{gen},i} - \sum_{i=1}^{n} P_{mg,i} \times \text{COE}_{mg,i} \right\} \quad (9)$$

where $P_{\text{gen},i}$ is the power generated by DG, $P_{mg,i}$ is the total power generated by the components that make up the proposed microgrid system, $\text{COE}_{\text{gen},i}$ is the COE from using the DG to meet load demand and $\text{COE}_{mg,i}$ is the COE from the proposed microgrid system.

The maintenance cost benefit because of incorporating RETs into the existing power system can be expressed as

$$\text{MC}_{\text{benefit},i} = \left\{ \sum_{i=1}^{n} \text{MC}_{\text{gen},i} - \sum_{i=1}^{n} \text{MC}_{mg,i} \right\} \quad (10)$$

where $\text{MC}_{\text{gen},i}$ is the maintenance cost by utilising only DG and $\text{MC}_{mg,i}$ is the total maintenance cost after introduction of green energy technologies into the power system.

The fuel cost benefit is expressed as

$$\text{FC}_{\text{benefit},i} = \left\{ \sum_{i=1}^{n} \text{FC}_{\text{gen},i} - \sum_{i=1}^{n} \text{FC}_{mg,i} \right\} \quad (11)$$

where $\text{FC}_{\text{gen},i}$ is the fuel cost by utilising only DG and $\text{FC}_{mg,i}$ is the total fuel cost with the application of green energy technologies.

The emission cost benefit is expressed as

$$\text{EC}_{\text{benefit},i} = \left\{ \sum_{i=1}^{n} \text{EC}_{\text{gen},i} - \sum_{i=1}^{n} \text{EC}_{mg,i} \right\} \quad (12)$$

where $\text{EC}_{\text{gen},i}$ is the emission cost by utilising only DG and $\text{EC}_{mg,i}$ is the total emission cost after incorporating RETs into the proposed power system.

The second element of the objective function is summarised as

$$\sum_{i=1}^{4} \text{TB}_i = \sum_{i=1,j=1}^{4} \left\{ \sum_{i=1}^{n} \sum_{j=1}^{m} k_{j,i} - \sum_{i=1}^{n} \sum_{j=1}^{m} z_{j,i} \right\} \quad (13)$$

where $k_{1,i}$, $k_{2,i}$, $k_{3,i}$, $k_{4,i}$ and $k_{5,i}$ represent maintenance cost, emission cost, fuel cost and electricity cost before incorporating PV, WTG and ESS into the power system. While $z_{1,i}$, $z_{2,i}$, $z_{3,i}$, $z_{4,i}$ and $z_{5,i}$ show the maintenance cost, emission cost, fuel cost and electricity cost after integration of PV, WTG and ESS into the proposed microgrid system.

The index that reflects the benefit share in the study is applied to estimate the benefit of one generation unit in proportion to the entire power system

$$\underset{G_i}{\text{MBS}} = \frac{P_i}{\sum_{i=1}^{n} P_i} \times \sum_{i=1}^{4} \text{TB}_i \quad (14)$$

where $\sum_{i=1}^{n} P_i$ is the variable that represents the sum of power generated from the entire system, G_i is the electricity generated by unit i, P_i is the power generation of G_i and n is the number of electricity generation units.

The third and fourth elements of the objective are introduced in the study to maximise the usage of RETs. This is achieved with the estimation of the yearly average PV and WTG power generation from solar and wind resources. The output power from the WTG and PV can be simulated by utilising their specific metrics. In this study, a yearly time frame is used to stimulate the renewable energy generation from the PV and WTG systems.

The yearly average power generation from the PV can be presented as follows:

$$f_{\text{obj3},i} = Y_{\text{pv},jy} = \frac{1}{8760} \sum_{t=1}^{8760} \left(\frac{P_{\text{pv},jy}}{P_{\text{pv},jy}^{\max}} \right) \quad (15)$$

where $Y_{\text{pv},jy}$ is the average PV generation of year j, $P_{\text{pv},jy}$ is the power produced from the PV farm at time t in year j and $P_{\text{pv},jy}^{\max}$ depicts the maximum value of yearly average PV generation.

The yearly average wind power generation from the WTG can be expressed as follows:

$$f_{\text{obj4},i} = Y_{\text{wtg},jy} = \frac{1}{8760} \sum_{t=1}^{8760} \left(\frac{P_{\text{wtg},jy}}{P_{\text{wtg},jy}^{\max}} \right) \quad (16)$$

where $Y_{\text{wtg},jy}$ is the average wind generation of year j, $P_{\text{wtg},jy}$ is the power produced from the wind farm at time t in year j and $P_{\text{wtg},jy}^{\max}$ depicts the maximum value of yearly average wind generation.

The fifth element of the objective function is to minimise the usage of DG. This can be achieved with the estimation of yearly average power generation from the DG that is presented in (17) as

$$f_{\text{obj5},i} = Y_{\text{gen},jy} = \frac{1}{8760} \sum_{t=1}^{8760} \left(\frac{P_{\text{gen},jy}}{P_{\text{gen},jy}^{\max}} \right) \quad (17)$$

where $Y_{\text{gen},jy}$ is the average DG generation of year j, $P_{\text{gen},jy}$ is the power produced from the DG at time t in year j and $P_{\text{gen},jy}^{\max}$ depicts the maximum value of yearly average DG generation.

3.1 Power system constraints

The main goal of utilising constraints in the power system is to provide the utilities with the necessary information to optimise the performance of the system in line with various objectives. The typical objectives to be achieved with the utilisation of power system constraints have been stated in Section 3. The objective functions proposed in this research work are structured to operate between the minimum and maximum operating limits of the generating units based on the specifications of manufacturers. The power-generating limits, SOC of the ESS and power balance are taken into consideration in the proposed microgrid system. The constraints of the power system meticulously considered in this research work are expressed as follows.

3.1.1 Power system balance constraint: In this paper, the economic operation can be achieved, if it takes the dispatched power of each component of a microgrid system as the input with the goal of accomplishing the objective of the research work. The power generated from multiple sources such as PV, WTG, DG and ESS structures units to meet the power requirement. The objective function of the study is subject to the following power balance:

$$\sum_{i=1}^{n} P_{\text{gen},i} + \sum_{i=1}^{n} P_{\text{pv},i} + \sum_{i=1}^{n} P_{\text{wtg},i} - \sum P_{\text{ess}}^{c} + P_{\text{ess}}^{d} = P_L \qquad (18)$$

where P_L represents the power demand at time t while P_{ess}^{c} and P_{ess}^{d} are control variables that represent charging and discharging energy of the ESS at time t, respectively.

The total power generated by the PV and WTG units is another constraint of the problem that needs to be less than or equal to the rated values of PV and WTG. This will improve the durability and performance of the aforementioned power sources. It is presented as

$$\left(P_{\text{pv}} + P_{\text{wtg}} + P_{\text{ess}}^{c}\right) \le \left(P_{\text{pv}}^{r} + P_{\text{wtg}}^{r}\right) \qquad (19)$$

where P_{wtg}^{r} and P_{pv}^{r} are the rated power of the WTG and PV based on the manufacturers' technical specifications.

Another constraint of the problem is that the total energy generated by the solar and wind units should be more or equal to that of the energy demand of the consumers. It can be represented as

$$\left\{\sum_{t=1}^{n}\left(P_{\text{pv}}^{t} \times \Delta t\right) + \sum_{t=1}^{n}\left(P_{\text{wtg}}^{t} \times \Delta t\right) \ge \sum_{t=1}^{n}\left(P_{L}^{t} \times \Delta t\right)\right\} \qquad (20)$$

3.1.2 Power generating limits: The selected power generating components of the proposed power system are scheduled to operate between the minimum and maximum limits to avoid load shedding and power curtailment. It will enhance the durability of the power system and also reduce the maintenance cost. The minimum and maximum constraints of the DG, PV, WTG and ESS are stated:

$$\begin{cases} P_{\text{gen}}^{\min} \le P_{\text{gen}} \le P_{\text{gen}}^{\max}, \\ P_{\text{pv}}^{\min} \le P_{\text{pv}} \le P_{\text{pv}}^{\max}, \\ P_{\text{wtg}}^{\min} \le P_{\text{wtg}} \le P_{\text{wtg}}^{\max}, \\ P_{\text{ess}}^{c,\min} \le P_{\text{ess}} \le P_{\text{ess}}^{c,\max} \text{ and} \\ P_{\text{ess}}^{d,\min} \le P_{\text{ess}} \le P_{\text{ess}}^{d,\max} \end{cases} \qquad (21)$$

3.2 Optimisation technique

The fmicon optimiser in the MATLAB toolbox is utilised in the study to minimise the multi-objective functions of the power system subject to lower and upper bound limits and non-linear inequality constraints. The objective function of the study with the fmincon solver is presented as

$$\min_{x} f(x) \text{ such that } \begin{cases} \boldsymbol{c}(x) \le 0 \\ \boldsymbol{ceq}(x) = 0 \\ \boldsymbol{A} \cdot x \le \boldsymbol{b} \\ Aeq \cdot x = \boldsymbol{beq} \\ lb \le x \le ub \end{cases} \qquad (22)$$

where $\boldsymbol{b}$ and $\boldsymbol{beq}$ are vectors, $\boldsymbol{A}$ and $\boldsymbol{Aeq}$ are matrices, $\boldsymbol{c}(x)$ and $\boldsymbol{ceq}(x)$ are functions that return vectors, $f(x)$ is a function that returns a scalar and lb and ub are lower and upper bound limits. $f(x)$, $\boldsymbol{c}(x)$ and $\boldsymbol{ceq}(x)$ can be non-linear functions.

4 Economic evaluation of a microgrid system

The technical and economic analyses of a microgrid system are introduced in this study by using some KPIs. The economic performance of the power system is assessed by utilising the actual overall cost of all the components of the system, load profile, and solar and wind resources data from South Africa Weather Service. The load profile of a typical load in Cape Town, South Africa is utilised in the work. The economic performance indicators presented in the study can be utilised to compare the results as a measure to accomplish a specific level of sustainability. This will maximise the profit margin of most of the IPPs and improve the performance of their systems. The economic indicators proposed in the study consider the detail comparison between the actual costs of the major components, emission cost, fuel cost and operation and maintenance cost.

4.1 Capital cost

The capital cost of a sustainable energy with the application of RETs depends on the number of the PV panels (n_{pv}), WTG (n_{wtg}), ESS (n_{ess}), Cov (n_{cov}) and DG (n_{gen}) and it can be estimated by using

$$C_{\text{capital}} = \text{CRF}\left\{\begin{array}{c} n_{\text{pv}}C_{\text{cap,pv}} + n_{\text{wtg}}C_{\text{cap,wtg}} \\ +n_{\text{ess}}C_{\text{cap,ess}} + n_{\text{gen}}C_{\text{cap,gen}} + n_{\text{con}}C_{\text{cap,con}} \end{array}\right\} \qquad (23)$$

where $C_{\text{cap,wtg}}$, $C_{\text{cap,pv}}$, $C_{\text{cap,ess}}$, $C_{\text{cap,gen}}$ and $C_{\text{cap,con}}$ are the unit costs of the WTG, PV, ESS, DG and converter.

4.1.1 Capital recovery factor (CRF): The CRF can be estimated with the utilisation of the life span of the component (n) and interest rate (i) [22]

$$\text{CRF} = \frac{i(i+1)^n}{(1+i)^n - 1} \qquad (24)$$

4.1.2 Replacement cost: The replacement cost is the cost required to replace the components of a microgrid system according to its current market worth. It can be estimated by using

$$C_{\text{repl}} = \text{SFF}\left\{\begin{array}{c} n_{\text{pv}}C_{\text{repl,pv}} + n_{\text{wtg}}C_{\text{repl,wtg}} \\ +n_{\text{ess}}C_{\text{repl,ess}} + n_{\text{gen}}C_{\text{repl,gen}} + n_{\text{con}}C_{\text{repl,con}} \end{array}\right\} \qquad (25)$$

where SFF is the sinking fund factor and $C_{\text{repl,wtg}}$, $C_{\text{repl,pv}}$, $C_{\text{repl,gen}}$ $C_{\text{repl,ess}}$ and $C_{\text{repl,gen}}$ are the unit costs of the WTG, PV, DG, ESS and converter.

The sinking fund factor can be expressed as

$$\text{SFF} = \frac{i}{(1+i)^n - 1} \qquad (26)$$

4.2 Maintenance cost

Maintenance cost is the cost incurred to keep the components of a microgrid system in a good working condition. The total annual maintenance cost is presented as

$$C_m = \left\{\begin{array}{c} C_{m,\text{pv}} \times \sum_{t=1}^{n}\left(P_{\text{pv}}^{t} \times \Delta t\right) + C_{m,\text{wtg}} \times \sum_{t=1}^{n}\left(P_{\text{wtg}}^{t} \times \Delta t\right) \\ +C_{m,\text{ess}} \times \sum_{t=1}^{n}\left(P_{\text{ess}}^{t} \times \Delta t\right) + C_{m,\text{gen}} \times \sum_{t=1}^{n}\left(P_{\text{gen}}^{t} \times \Delta t\right) \\ +C_{m,\text{con}} \times \sum_{t=1}^{n}\left(P_{\text{con}}^{t} \times \Delta t\right) \end{array}\right\} \qquad (27)$$

where $C_{m,\text{wtg}}$, $C_{m,\text{pv}}$, $C_{m,\text{gen}}$ $C_{m,\text{ess}}$ and $C_{m,\text{con}}$ are the maintenance cost of the WTG, PV, DG, ESS and converter.

4.3 Fuel cost

DG can be used by the IPPs for peak shaving, emergency, standby and standalone operations. The acceptance of DG for the aforementioned operation is attributed to the following characteristics: durability, readily available, quick start up, reliability and so on. The DG produces electricity on demand, but the major challenge of the DG is fuel cost (FC), emissions cost and maintenance cost. In this section, it is explained the FC that carries the prevalent share of the total cost of a microgrid system. The FC of the DG depends on the rating of the DG, the capacity of the connected load, humidity, the quality of the fuel and operating temperature. The FC of the DG can be expressed as

$$\text{FC} = \sum_{i=1}^{n} a_i + b_i P_{\text{gen},i} + c_i P_{\text{gen},i}^2 \tag{28}$$

where $P_{\text{DG},i}$ is the power produced by the DG and a, b and c are cost coefficients of the DG.

The power generated by the DG must be within the operating limits as presented in (28)

$$P_{\text{gen},i}^{\min} \le P_{\text{gen},i} \le P_{\text{gen},i}^{\max} \tag{29}$$

$P_{\text{gen},i}^{\min}$ and $P_{\text{gen},i}^{\max}$ are the minimum and maximum operating rated capacities of the DG specified by the manufacturers.

4.4 Cost of energy

The COE is one of the performance benchmarks that can be used by the MGOs to estimate the economic feasibility of a microgrid system. The COE is measured based on the annualised TCS and annual energy production (AEP). The COE can be estimated by utilising the following expression:

$$\text{COE} = \frac{\text{TCS}}{\text{AEP}} (\$/\text{kWh}) \tag{30}$$

5 Environmental evaluation of a microgrid system

The GHG pollutions that are associated with the commercial, industrial, transportation and power generation activities are overloading the atmosphere with global warming emissions. These gases act as a trapping and blanket heat that cause many health hazards. Different sources of fossil fuels such as natural gas, coal, oil and diesel produce environmental hazards based on their chemical compositions, type of technology utilised to produce electricity, geographical locations and type of cooling system. The green energy technologies do not produce direct global warming emissions. The incorporation of RETs into the traditional power system will allow the power utilities to replace GHG emission-intensive power plants and considerably reduce global warming emissions. The application of RETs can reduce the electricity sector's emission by ∼81% and substantially reduce air pollution, wildlife' habitat loss, degradation of soil, damage to public health and water pollution [13]. The impacts of GHG emission from the conventional power stations can be drastically reduced by directly generating electricity from clean sources such as solar, wind, biomass and tides.

5.1 Emission cost

The energy mix with the integration of RETs can assist the MGOs to satisfy the power requirement in a circumstance where the local wind and solar resources are readily available. The GHG footprint can be reduced drastically by directly generating power from clean, renewable energy sources since green energy technologies produce no direct emissions from fossil fuels and reduce air pollution. In this section, the comparison of different sources of GHG emissions is made by using carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxide (NOx). The environmental effects of the RETs on the operation of the power system are assessed by using emission cost. The emission cost that is the hourly summation of CO_2, SO_2 and NOx emissions is expressed as

$$C_{\text{emission}} = \sum_{i=1}^{m} \sum_{j=1}^{n} \left\{ \begin{array}{l} PF_j P_{\text{gen},i} E_{ij} \text{CO}_{2,G_i(t)} \\ +PF_j P_{\text{gen},i} E_{ij} \text{SO}_{2,G_i(t)} \\ +PF_j P_{\text{gen},i} E_{ij} \text{NO}_{x,G_i(t)} \end{array} \right\} \tag{31}$$

where P_{gen} is the power generated by the DG, PFj is the externality costs of emission type j of the DG unit, m is the emission types CO_2, SO_2 and NO_x. While $CO_{2,Gi(t)}$, $SO_{2,Gi(t)}$ and $NO_{x,Gi(t)}$ are the emissions from the DG source (G_i) at time t. Eij is the emission factor of the DG unit i and emission type j, and n is the number of DG.

6 Design parameters of the proposed microgrid system and its specifications

The microgrid system proposed in the study encompasses four important components such as DG, ESS, PV, ESS and WTG. The above components can test the economic performance of the power system; therefore, this forms a significant segment of the optimisation problem of a microgrid system [28–30]. It centres this paper on the application of optimising toolbox in the MATLAB to optimise the power system problem with multi-objective functions. The operating and economic parameters used for this research work are presented in Table 1.

7 Numerical results and discussions

The fmincon is used in the study to obtain the optimised results from a DG, PV, WTG and ESS microgrid system. The above-mentioned method is applied to optimise the major components of the objective function as presented in (5). The green energy technologies are utilised in the study to minimise the TCS that is one of the critical components of a microgrid system. The impacts of sustainable energy technologies in a power system can be evaluated based on the values of TCS and other KPIs. The impacts of RETs in a microgrid system are investigated in this section as a measure to authenticate the feasibility and effectiveness of the proposed optimisation method. The simulation results obtained from the study are presented as follows:

Case study 1: The economic and environmental analysis of this case study is implemented without utilising green technologies. It is well established from the global records that the DG operates with the exceedingly high fuel cost, emissions and maintenance cost. This has limited the universal acceptance of the DG to provide power solutions in some locations. The DG is used in this scenario based on the power requirements and power output of the DG as presented in Figs. 2*a* and *b*. The comparison between the power output of the DG and power demand indicates that consumers' load demand totally depends on the operation of the DG with the TCS of 236,190 \$/year, capital cost of 74,880 \$/year, maintenance cost of 23,172 \$/year, emission cost of 7623.4 \$/year and fuel cost of 101,630 \$/year as presented in Fig. 3*a*. The value of TCS for this case study is high and its breakdown is presented in Figs. 3*a* and *b*. It can be established from Fig. 3*b* that fuel cost has the largest constituent of the TCS with about 43.03%. The fuel cost that has the largest share of the TCS as shown in Fig. 3*b* can be reduced with the application of RETs. This indicates that the operating cost of the DG is a function of the power demand because there is no other generating unit that can meet the load requirements. The results obtained from utilising the DG alone to satisfy the load demand indicates that the values of TCS, COE and yearly average DG power are exceedingly high owing to the operating parameters of the DG. Moreover, the emissions produced from utilisation of the DG to satisfy the power demand are presented in Table 2 while the COE is also presented in Table 3. The research work shows that the DG alone configuration is not environmentally and economically feasible due to the high fuel cost that has a considerable effect on the TCS. Owing to the results

Table 1 List of design parameters for the specified components [19, 22, 31]

Description	DG	PV	WTG	ESS
life span of the component	25,000 h	25 year	25 year	5 year
interest rate	6%	6%	6%	6%
cost of unit	$3825	$225	$2600	$145
maintenance cost	0.01258 $/kWh	0.5 cent/kWh	0.2 cent/kWh	11 $/year per unit
technical details		dimension = 1310 × 1950 mm max. power voltage and current = 48.6 V and 10.29 A open circuit voltage = 59.12 V short circuit current = 10.44 A and η_m = 19.48%		400 AH, 24 V, η_c = 90%, DOD = 40% and η_d = 40%.
capacity ratings	2 × 30 kW = 60 kW	84 × 0.5 kW = 42 kW	100 × 0.3 kW = 30 kW	2 kW@ 400 Ah

Emission costs and emission factors

Emissions	Emission factor, kg/kWh	Emission externality costs
CO_2	0.6569395	0.017
NOx	0.0066911	1.086
SO_2	0.0003595	1.8

η_c is the ESS charge efficiency, η_d is the ESS charge efficiency and η_m is the PV module efficiency.

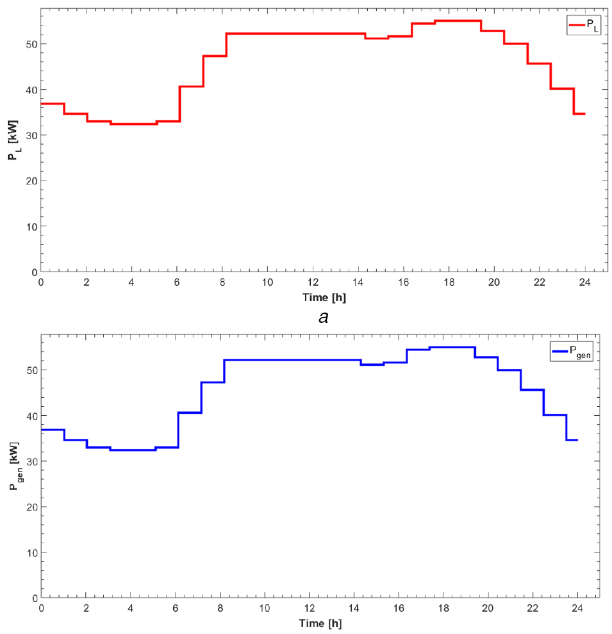

Fig. 2 *Power output of the DG and consumers' load demand for the case study 1*
(a) Power demand by the consumers at the load point on hourly basis, ***(b)*** Power produced by utilising the DG in the absence of PV, WTG and ESS

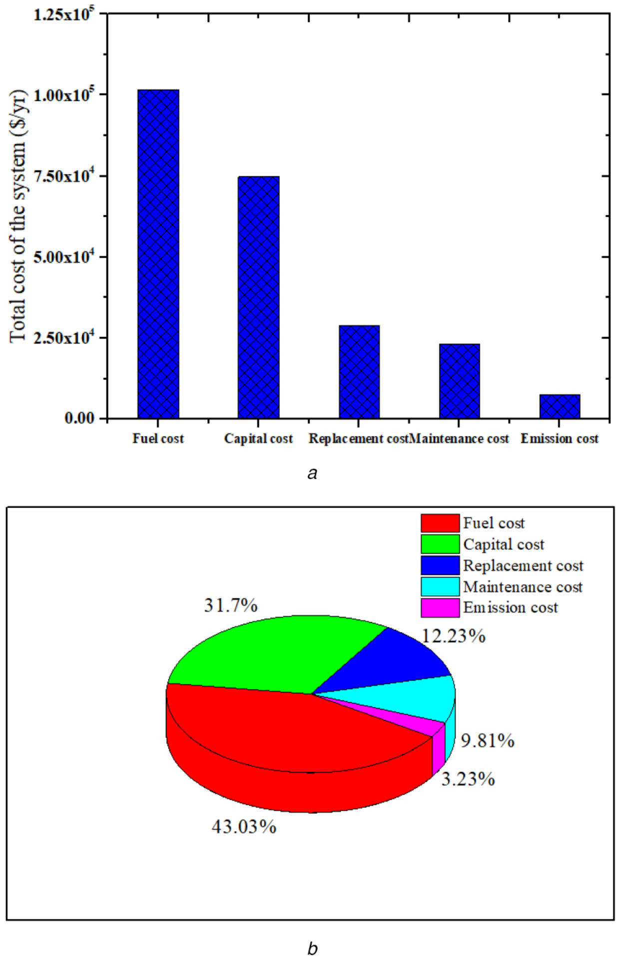

Fig. 3 *Components of total cost of the system for case study 1*
(a) Breakdown of total cost of the system got without the PV, WTG and ESS by carrying out performance analysis of the system, ***(b)*** Percentage of breakdown of total cost of the system got without PV, WTG and ESS by carrying out performance analysis of the system

Table 2 Economic and environmental analysis of the proposed microgrid system

Description	Microgrid system with DG	Microgrid system with DG, PV, WTG and ESS	Cost savings
TCS ($/year)	235,360	162,750	72,610
fuel ($/year)	101,630	41,263	60,367
capital ($/year)	74,880	83,731	−8851
replacement ($/year)	28,884	29,139	−255
maintenance ($/year)	23,172	6702.1	16,469.9
emission ($/year)	7623.4	1915	5708.4
CO_2 (kg/year)	262,460	65,929	196,531
NOx (kg/year)	2673.2	671.504	2001.696
SO_2 (kg/year)	143.625	36.0786	107.5464
fuel (L/year)	101,630	41,263	60,367

obtained by using the DG alone, the GHG emissions and COE that have become a public concern for decades can be reduced to a substantial value with the utilisation of green energy technologies.

Case study 2: The techno-economic assessment of a microgrid system is implemented in this scenario with the application of the DG, PV, ESS and WTG. The output power of all the components of a microgrid system is presented in Fig. 4*a* and the SOC of the ESS is shown in Fig. 4*b*. They use the green energy technologies in this scenario to minimise the TCS, total benefits and yearly average power generation of the power system. The technique applied in this research work permits the ESS to be charged whenever there is

Table 3 Impacts of integrating a number of PV, WTG and ESS units on the proposed microgrid system

Description	Microgrid system with DG	Microgrid system with DG, PV, WTG and ESS
$f_{obj1,i}$($)	236,190	162,750
$f_{obj2,i}$($)	—	155,990
$f_{obj3,i}$(kW)	—	0.4404
$f_{obj4,i}$(kW)	—	0.5718
$f_{obj5,i}$(kW)	0.7601	0.1909
COE ($/kWh)	0.433	0.2716
MBS_DG ($)	—	39,184
MBS_PV ($)	—	66,284
MBS_WTG ($)	—	49,891
MBS_ESS ($)	—	628.7298

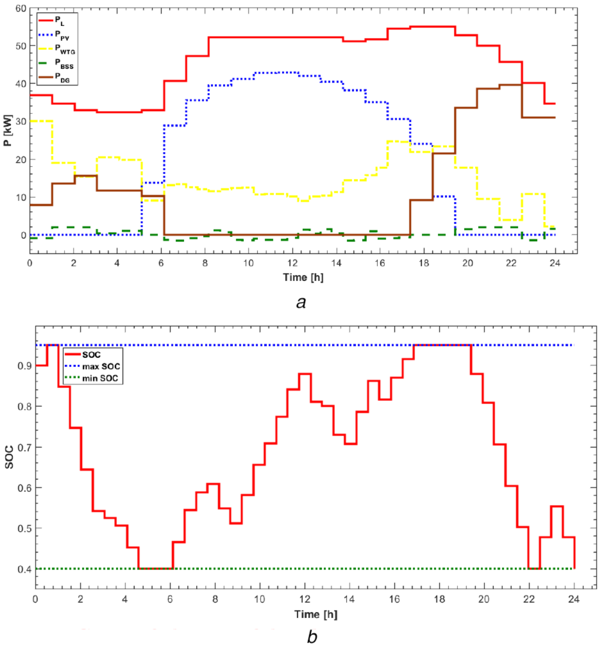

Fig. 4 *Optimum power flow of DG, PV, WTG and ESS and SOC of ESS for case study 2*
(a) Power produced by each component of the power system such as DG, PV, WTG and ESS, ***(b)*** SOC of the ESS

an excess power generated from the WTG and PV. This shows that the ESS will be discharged once the power demand surpasses the total power generated by the WTG and PV. It is designing the DG in this scenario to generate the deficient power demand once the power outputs of the WTG, PV and ESS do not satisfy the power requirements. The power generation from the DG has drastically reduced as shown in Fig. 4*a*. This shows that DG is scheduled to operate early in the morning and 3 pm to 7 am with a unit of DG. There is a total shutdown of the DG between 6 am to 3 pm owing to wind and solar resources. During this time, the output of WTG and PV units can satisfy the load demand while it is used the excess electrical power to charge the ESS. The two units of the DG will run concurrently from 8 pm to midnight owing to the absence of power output from the PV system. This shows that power demand depends on the DG, ESS and WTG.

The results obtained in this scenario with some KPIs are presented: TCS of $162,750/year, C_m of $6702.1/year, C_{fuel} of $41,263/year, C_{emission} of $1915/year, C_{capital} of $83,731/year and C_{repl} replacement cost of $29,139/year as presented in Table 2. This shows that the values of TCS, C_m, C_{fuel} and C_{emission} have reduced by 30.85, 71.08, 59.40 and 74.88%, respectively, while the value of C_{capital} has marginally increased by 11.82% owing to integration of additional units of RETs. The utilisation of RETs has considerably

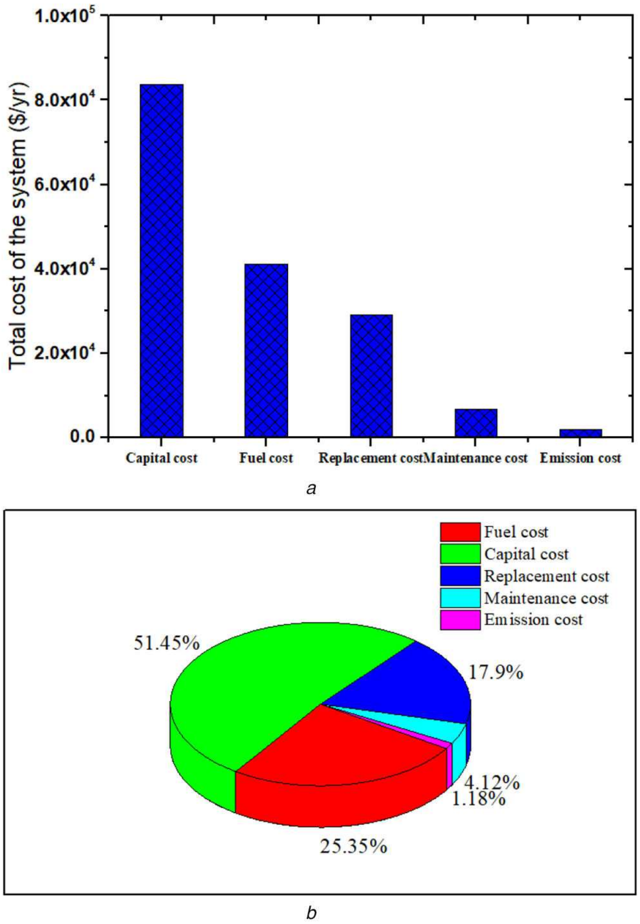

Fig. 5 *Components of total cost of the system for case study 2*
(a) Breakdown of total cost of the system obtained with DG, PV, WTG and ESS by carrying out performance analysis of the system, ***(b)*** Percentage of breakdown of total cost of the system obtained with DG, PV, WTG and ESS by carrying out performance analysis of the system

enhanced the optimal operation of the proposed DG-PV-WTG-ESS microgrid system over the time horizon of the project. Besides this, the application of green energy technologies in the existing power system has increased the yearly average WTG and PV power generation and reduced the yearly average DG power generation as presented in Table 3. In addition, the MBSs of the unit *i* that reflects the benefit of one generation unit in proportion to it presents the whole power system in Table 3. It can be seen that PV has the highest MBS, followed by WTG. In addition, the breakdown of TCS is presented in Fig. 5*a*, it can be established that the major components of the TCS have reduced substantially with the application of RETs as shown in Fig. 5*b*. This shows that special preference should be given to green energy technologies when planning and designing energy mix.

The cost savings that are identified with the operation of a DG-PV-WTG-ESS microgrid system are shown in Fig. 6. The simulation results from the research work show that microgrid configuration with RETs is economically and environmentally workable owing to optimised values of TCS, COE, C_m, C_{fuel} and C_{emission}. This can reduce the operating cost and GHG emissions coupled with the associated environmental effects of conventional power system. It is highly interested to observe that the cost-effective power solution is provided with the application of the WTG, PV, ESS and DG. This shows that the technique applied in the study is appropriate to solve multi-objective function problems.

8 Comparison with other existing methods

The robustness and efficiency of the fmincon optimiser in solving a multi-aim problem is shown by comparing the results derived from the study with other research works where the well-known heuristic algorithms were used. The importance of the algorithm

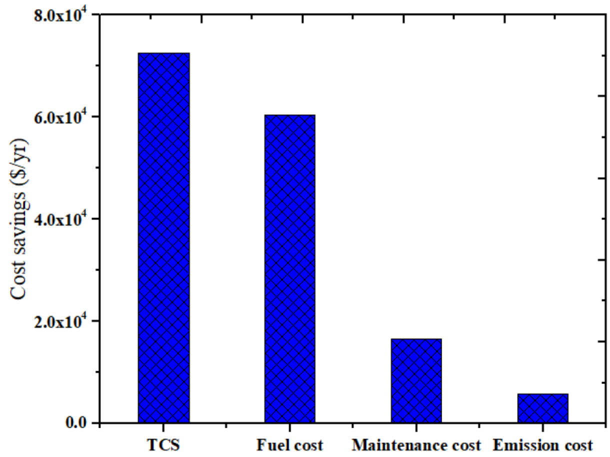

Fig. 6 *Effect of PV, WTG and ESS on the cost savings of a microgrid system*

Table 4 Comparison of the present algorithm with many already established heuristic algorithms

System architecture	DG	BG	PV	WTG	ESS	PHES	Technique	COE, $/kWh
the present research work	✓	×	✓	✓	✓	×	fmincon	0.2716
SHES [9]	✓	×	✓	×	✓	×	GA	0.28
SPS [32]	✓	×	✓	✓	✓	×	SPEA	0.84
OCPS [33]	✓	×	✓	×	✓	×	SA-GIS	0.4441
SPS [34]	✓	×	✓	×	✓	×	HS-GIS	0.4571
OCPS [35]	✓	×	✓	×	✓	×	IHS-SA-GIS	0.4732
OCPS [36]	×	✓	✓	×	✓	✓	WCA	0.4864
SPS [37]	×	—	✓	×	✓	✓	FA	0.5611

BG, biogas generator; FA, firefly algorithm; GA, genetic algorithm; GWO, grey wolf optimisation; HS, harmony search; HS-GIS, harmony search-geographical system; IHS-SA-GIS, improved harmony search-simulated annealing-geographical system; OCPS, off-grid connected power system; PHES, pumped hydro energy storage; SA-GIS, simulated annealing-geographical system, SHES, standalone hybrid energy systems; SPEA, strength pareto evolutionary algorithm; SPS, standalone power system; WCA, water cycle algorithm.

presented in the paper can be easily understood by comparing the most optimised configuration of the study with other works to highlight its novelty. It is compared to performing the optimal configuration of the present study with the other configurations that operate under similar conditions but with the same configuration or difference in the system configuration. The comparison is made by using the COE generic to the optimal operation of the power system which is shown in Table 4. It well established that the COE derived from the present study is lower than the one got in [9, 32–37]. Hence, the optimisation technique presented in the paper has resulted in a cost-effective design to reduce the techno-economic costs that are associated with the proposed microgrid system when compared with the configurations found in literature. From the above discussion, the novelty of this work is established based on the comparison with similar studies that have used different heuristic algorithms and configurations and the affordable COE got from the optimised configuration of the research work.

9 Conclusion

The green energy technologies have become the universal power solution that can be incorporated into the traditional power system to maximise the efficiency of the power system and ensure the accessibility of electricity at all times. The performance of the power system can be improved by upgrading the existing traditional power system by integrating green energy technologies and smart grid features. It is reported from the study that the power generated from a DG-PV-WTG-ESS microgrid system is an effective way of using sustainable energy for a standalone power system that can be used for rural electrification projects. The high cost of diesel, coupled with the expansion of T&D lines is not a cost-effective solution to satisfy standalone load demand. Therefore, integration of RETs has become a workable alternative for a standalone power system. The MGOs can purposely design the microgrid system to serve the specific needs of rural areas. Proper planning can accomplish the sustainability of power supply in the remote communities RETs in a microgrid system. This will enhance the standard of living of the rural dwellers that have no access to the utility power supply owing to the economics of scale. The results got from the study show the MGOs can use that to optimise the costs that are identified with their power systems, provided it provides the information about the proposed power systems. The activeness of RETs to reduce the fuel cost, emission, maintenance cost, COE, and the total cost was investigated in the study. The simulation results prove the effectiveness of RETs in the power system. The proposed microgrid system has become a cost-effective and environmentally friendly power solution to improve access to electricity. The results obtained from the strategic operation applied in this work achieved the best performance and can be used as the standards to test the performance of a microgrid system. The international agencies can use the outcomes of the study as the standard to harness the potential benefits of solar and wind resources for strategic planning and designing of rural electrification projects and power sector restructuring. The model presented in the research work will act as a baseline to monitor the performance of a microgrid system having considered government policies and design specifications.

10 References

[1] Adefarati, T., Bansal, R.C.: 'Integration of renewable distributed generators into the distribution system: a review', *IET Renew. Power Gener.*, 2016, **10**, (7), pp. 873–884

[2] Adefarati, T., Bansal, R.C.: 'The impacts of PV-wind-diesel-electric storage hybrid system on the reliability of a power system', *Energy Procedia*, 2017, **105**, pp. 616–621

[3] Adefarati, T., Bansal, R.C.: 'Reliability and economic assessment of a microgrid power system with integrating renewable energy resources', *Appl. Energy*, 2017, **206**, pp. 911–933

[4] Khan, F., Pal, N., Saeed, S.: 'Review of solar photovoltaic and wind hybrid energy systems for sizing strategies optimization techniques and cost analysis methodologies', *Renew. Energy Rev.*, 2018, **92**, pp. 937–947

[5] Adefarati, T., Bansal, R.C, Justo, J.J.: 'Techno-economic analysis of a PV–wind–battery–diesel standalone power system in a remote area', *J. Eng.*, 2017, **2017**, (13), pp. 740–744

[6] Adefarati, T., Bansal, R.C, Justo, J.J.: 'Reliability and economic evaluation of a microgrid power system', *Energy Procedia*, 2017, **142**, pp. 43–48

[7] Tazvinga, H., Thopil, M., Numbi, P.B., *et al.*: 'Distributed renewable energy technologies', in Bansal, R.C. (Ed.): '*Handbook of distributed generation*' (Springer International publishing, Cham, Switzerland, 2017), pp. 3–67
[8] Nadjemi, O., Nacer, T., Hamidat, A., *et al.*: 'Optimal hybrid PV/wind energy system sizing: application of cuckoo search algorithm for Algerian dairy farms', *Renew. Sust. Energy Rev.*, 2017, **70**, pp. 1352–1365
[9] Das, B.K., Al-Abdeli, Y.M., Kothapalli, G.: 'Optimization of standalone hybrid energy systems supplemented by combustion-based prime movers', *Appl. Energy*, 2017, **196**, pp. 18–33
[10] Cristóbal-Monreal, I.R., Dufo-López, R.: 'Optimization of photovoltaic–diesel–battery standalone systems minimizing system weight', *Energy Convers. Manage.*, 2016, **119**, pp. 279–288
[11] Kim, W., Shin, J., Kim, S., *et al.*: 'Operation scheduling for an energy storage system considering reliability and aging', *Energy*, 2017, **141**, pp. 389–397
[12] Liu, M., Li, W., Wang, C., *et al.*: 'Reliability evaluation of large-scale battery energy storage systems', *IEEE Trans. Smart Grid*, 2017, **8**, pp. 2733–2743
[13] Cicilio, P., Orosz, M., Mueller, A., *et al.*: 'Ugrid: reliable minigrid design and planning toolset for rural electrification', *IEEE Access*, 2019, **7**, pp. 163988–163999
[14] Li, B., Roche, R., Damien Paire, D., *et al.*: 'Sizing of a standalone microgrid considering electric power, cooling/ heating, hydrogen loads and hydrogen storage degradation', *Appl. Energy*, 2017, **205**, pp. 1244–1259
[15] Zhang, Y., Campana, P.E., Lundblad, A., *et al.*: 'Comparative study of hydrogen storage and battery storage in grid connected photovoltaic system: storage sizing and rule-based operation', *Appl. Energy*, 2017, **201**, pp. 397–411
[16] Zhao, B., Zhang, X., Li, P., *et al.*: 'Optimal sizing, operating strategy and operational experience of a standalone microgrid on Dongfushan Island', *Appl. Energy*, 2014, **113**, pp. 1656–1666
[17] Nojavan, S., Majidi, M., Esfetanaj, N.N.: 'An efficient cost-reliability optimization model 44 for optimal siting and sizing of energy storage system in a microgrid in the presence of responsible load management', *Energy*, 2017, **139**, pp. 89–97
[18] Ogunjuyigbe, A.S.O., Ayodele, T.R., Akinola, O.A.: '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**, pp. 153–171
[19] Adefarati, T., Bansal, R.C.: 'Reliability, economic and environmental analysis of a microgrid system in the presence of renewable energy resources', *Appl. Energy*, 2019, **236**, pp. 1089–1114
[20] Ghenai, C., Bettayeb, M.: 'Modelling and performance analysis of a standalone hybrid soalr PV/fuel cell/DG power system university building', *Energy*, 2019, **171**, pp. 180–189
[21] Ghenai, C., Bettayeb, M.: 'Optimized design and control of an off grid solar PV/hydrogen fuel cell power system for green buildings'. 2nd Int. Conf. on New Energy and Future Energy System, (NEFES), Kunming, China, 22–25 September 2017
[22] Adefarati, T., Bansal, R.C.: 'Reliability assessment of distribution system with the integration of renewable distributed generation', *Appl. Energy*, 2017, **185**, pp. 158–171
[23] Kabir, M.N., Mishra, Y., Bansal, R.C.: 'Probabilistic load flow for distribution systems with uncertain PV generation', *Appl. Energy*, 2016, **163**, pp. 343–351
[24] Gidwani, L., Tiwari, H., Bansal, R.C.: 'Improving power quality of wind energy conversion system with unconventional power electronic interface', *Int. J. Electr. Power Energy Syst.*, 2013, **44**, (1), pp. 445–453
[25] Bansal, R.C., Bhatti, T.S., Kothari, D.P.: 'Some aspects of grid connected wind electric energy conversion systems', *Interdiscip. J. Inst. Eng. (India)*, 2001, **82**, (1), pp. 25–28
[26] 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**, pp. 266–276
[27] Carew, N., Warnock, W., Bayindir, R., *et al.*: 'Analysis of pumped hydroelectric energy storage for large-scale wind energy integration', *Int. J. Electr. Eng. Educ.*, 2020, pp. 1–14, https://doi.org/10.1177/0020720920928456
[28] Das, C.K., Bass, O., Kothapalli, G., *et al.*: 'Optimal placement of distributed energy storage systems in distribution networks using artificial bee colony algorithm', *Appl. Energy*, 2018, **232**, pp. 212–228
[29] Adefarati, T., Papy, N.B., Thopil, M., *et al.*: 'Non-renewable distributed generation technologies: a review', in Bansal, R.C. (Ed.): '*Handbook of distributed generation*' (Springer International publishing, Cham, Switzerland, 2017), pp. 69–105
[30] Bansal, R.C., Bhatti, T.S., Kumar, V.: 'Reactive power control of autonomous wind-diesel hybrid power systems using ANN'. Proc. 8th Int. Power Eng. Conf., Singapore, 3–6 December 2007, pp. 1376–1381
[31] Adefarati, T., Potgieter, S., Naidoo, R., *et al.*: 'Optimization of PV-wind-battery system storage microgrid system utilizing a genetic algorithm'. Proc. IEEE 7th Int. Conf. on Clean Electrical Power (ICCEP), Otranto, Puglia, Italy, July 2019
[32] Dufo-López, R., Bernal-Agustín, J.L., Yusta-Loyo, J.M., *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**, pp. 4033–4041
[33] Hafeznia, H., Yousefi, H., Astaraei, F.R.: 'A novel framework for the potential assessment of utility-scale photovoltaic solar energy, application to eastern Iran', *Energy Convers. Manage.*, 2017, **151**, pp. 240–258
[34] Pandiarajan, K., Babulal, C.: 'Fuzzy harmony search algorithm based optimal power flow for power system security enhancement', *Int. J. Electr. Power Energy Syst.*, 2016, **9**, pp. 72–79
[35] Cai, W., Li, X., Maleki, A., *et al.*: 'Optimal sizing and location based on economic parameters for an off-grid application of a hybrid system with photovoltaic, battery and diesel technology', *Energy*, 2020, **201**, p. 117480
[36] Das, M., Singh, M.A.K., Biswas, A.: 'Techno-economic optimization of an off-grid hybrid renewable energy system using metaheuristic optimization approaches – case of a radio transmitter station in India', *Energy Convers. Manage.*, 2019, **185**, pp. 339–352
[37] Biswas, A., Kumar, A.: 'Techno-economic optimization of a standalone PV/PHS/battery systems for very low load situation', *Int. J. Renew. Energy Res.*, 2017, **7**, (2), pp. 844–856