Assessment of renewable energy technologies in a standalone microgrid system

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Abstract: The rapid growth of the global economy has led to a high demand of electric energy and utilization of fossil fuels to meet the power demand. This has motivated the utilities or independent power providers to incorporate renewable energy resources (RERs) into their power systems. Moreover, with the increasing concerns of environmental protection and fossil fuel depletion, RERS are universally accepted as the potential alternative to fossil fuels. Consequently, this work aims at exploring the application of the photovoltaic (PV), electric storage system (ESS) and wind turbine generator (WTG) in a microgrid (MG) system to reduce the total annual cost (TAC) and environmental impact reduction index (EIR) while maintaining the power system constraints and load requirements. The problem is formulated by using the fmincon optimization solver in the MATLAB environment to assess the environmental and economic effects of utilizing RERs in a MG system. The values of TAC and EIR obtained in the study are compared with the base case study where a reciprocating engine is only utilized to meet the same power demand without using RERs and ESS. The results obtained from the study indicate that a WTG/PV/ ESS/ diesel generator MG system has achieved good results. The outcomes of the study demonstrate that utilization of green technologies is suitable for achieving global sustainable energy development.

Keywords: Battery storage system, economic efficiency, energy purchased, energy sold, net energy purchased.

Introduction

A recent survey demonstrated that the optimal operation of the microgrid systems with the application of green technologies has occupied a crucial position in the electric power sector. This is attributed to the rapid socio-economic growth and public concerns over the greenhouse gasses (GHGs) that emanated from the conventional power plants. Consequently, a considerable portion of electrical power must be generated from RERs. According to renewables 2018 global status report, about 26.5% of the energy utilized worldwide comes from RERs [1]. The estimation is based on the renewable energy share of global electricity production at the end of 2017. The electric power generation sector alone contributes up to 25% of the global GHG emissions [2]. Moreover, the burning of fossil fuels for transportation, industrial and power generation applications is responsible for the global GHG emissions and this has tremendously contributed to the ozone layer depletion, health hazard and soil degradation. The GHG emissions from the conventional power plants have attracted public attention in recent years owing to the increase in the smog, ozone pollution and climate change. This has prompted the Kyoto protocol to set an overall framework to limit global warming through the reduction of GHG emissions by 50-85% in 2050. The low carbon transition plan of July 2009 had also set out different measures to reduce the emissions of the power sector and heavy industry by 22% in 2020. Under this plan, power utilities have been forced to incorporate RERs into their power systems. This will ultimately lead to 40% of electricity to come from the low carbon sources. These arrangements have encouraged many countries in the world to have a sustainable and environmentally friendly power system [3].

The global power requirements have increased tremendously owing to rapid development in the global economy and population growth. The only alternative is to depend on the fossil fuel which is a source of GHG emission. This has motivated public outcry on energy efficiency and environmental protection. In view of this, many strategies for sustainable energy development and reduction of over dependence on fossil fuel have been implemented to improve energy efficiency and energy savings by using green technologies, switching to a cheaper energy tariff, shifting of the operation of certain equipment from the peak load period to off peak load period, replacement of incandescent bulbs with light emitting diode (LED) and compact fluorescent lamp (CFL) bulbs, utilizing energy efficient equipment, reduction of energy demand by monitoring daily energy consumption, smart energy solutions, etc. The most effective way to improve energy efficiency is with the application of green technology such as solar, wind, hydro, geothermal and biomass. The green technologies have numerous benefits when compared with the conventional sources, such as no fuel cost, reduction of operation and maintenance cost, no direct GHG emission, improved public health, less global warming, jobs creation, stable energy prices, safe and clean, reliable and resilience [3]. Moreover, the green technologies can be utilized in the areas where utility grid connection is difficult owing to financial and technical barriers. The green technologies have been taken as the potential solution to meet ever increasing global power demand based on some significant factors such as conceptual design, planning, price of electricity, operation and maintenance costs, etc. [4]. The aforementioned factors will assist the independent power providers to select the best option among the available renewable energy technologies. The power system planning will also assist the utilities to allocate their resources based on pattern of consumption, formulate the policies that will improve the reliability and security of power supply and defer the cost that is related to upgrading of transmission and distribution systems for development of economy [5].

The green energy technologies have been adjudged to be the most suitable power solution that can provide clean and sustainable electricity for the rural dwellers that are living in remote areas. This is attributed to some benefits and particular characteristics that make RETs to be suitable for a number of applications and locations. The economic and environmental benefits of RETs in a microgrid system depend on seasonal variation load demand and local wind and solar sources. The PV and WTG are universally accepted to be the most cost effective option for power generation in small-medium scale areas that are not connected to the utility grid. Moreover, for areas in which the solar and wind resources are adequately available, a microgrid system with the integration of WTG and PV is the potential power supply alternative when compared with the conventional generating units [3]. The application of renewable energy in a conventional power system has many technical and economic benefits on the global note. The benefits include a measure to reduce power consumption from the utility grid, reduce energy expenses, reduce the environmental impacts that associated with the operation of fossil fuel based power plants and improve operational efficiency. This will reduce the rate of utilizing non-natural replenish resources. However, RETs are capital intensive and their operations depend on weather and climatic conditions of a particular location. This demonstrates that RETs cannot continuously satisfy the load demand without some backup units such as diesel generator, battery system, water storage pump and microturbine. The fossil based generating units have quick start up, low capital cost and can produce electricity on demand, but not economically feasible based on high fuel cost, maintenance cost, cost of energy, GHG emissions, etc. [4]. The diesel generator and ESS that served as backup units in a microgrid system can operate optimally if it is combined with RETs [5]. This will make RETs to respond to load demand requirements due to the fact that available local renewable resources is a function of time and seasonal variation.

The configuration of a microgrid system has a significant impact on the optimal operation of a power system. The green technologies that consist of PV and WTG have gained universal acceptance as the potential choice to improve the energy efficiency as well as to reduce the impact of the GHG emissions, operating costs, fuel cost and maintenance cost that have become sources of the challenges for several distribution network operators [4]. The utilization of RERs in a power system has enhanced energy sustainability and provided a reliable electricity [5]. In addition to this, RERs allow consumers to save electricity costs by using the power generated from a MG system during the peak period when electricity tariff is high. This allows the networks to operate economically and efficiently as well as improves the monthly or yearly revenue of independent power providers. However, due to the intermittent characteristic of the solar and wind resources, it has posed a serious challenge to the power utilities [6]. Nevertheless, this can be overcome by utilizing the ESS in conjunction with the PV and WTG systems as a measure to smooth out the effects of stochastic characteristics of the local wind and solar resources in a MG system [7]. The power solution provided by the PV and WTG systems has increased considerably due to their environmentally friendly and low GHG emissions coupled with the low operation and maintenance (O&M) costs [8].

RERs have been the subject of numerous analysts in the past, with intention of minimizing the fuel and emission costs. The public concerns about the environmental effects of conventional power generation and depletion of fossil fuels have forced several researchers to develop many techniques for optimization of O&M costs and emissions with the incorporation of RERs into the power systems. Owing to this, Radosavljevic [9] has proposed the gravitational search algorithm and PSO for the optimization of fuel and emission costs of a MG system. Askari et al. [10] have investigated the impacts of utilizing the ESS and PV to improve the sustainability of power demand and to reduce the levelized cost of energy of a standalone system. Meanwhile, Bhandar et al. [11] have applied a linear programming technique to investigate the impact of the PV, hydropower and wind systems on the operation of a power system. The optimization results indicate that RERs are the most important alternatives to reduce the emission of a MG system. Moreover, Koussa et al. [12] have presented a method for economic assessment and GHG emission estimation of grid-connected RERs. The major challenge in the above-mentioned research work is the difficulty to structure the power system so as to meet the load demand having considered the non-linearity of power demand, solar and wind resources and fuel consumption of the diesel generator. In the aforementioned studies, the objective functions commonly utilized are the combination of fuel and emission costs without considering the capital and maintenance costs and EIR. The optimization model proposed in this work considers the variable nature of RERs, changes in demand and battery dynamics to investigate their impacts on minimization of the total annual cost (TAC), annual fuel cost$\left(C_{fuel,i}\right)$, annual GHG emission cost$\left(C_{emission,i}\right)$, annual maintenance cost $\left(C_{maint,i}\right)$ and annual capital cost $\left(C_{cap,i}\right)$ of a MG system. This has necessitated this study to be centred on the application of the fmincon optimization while considering changes in daily power demand. The model developed in this paper is utilized to maximize the usage of RERs at reduced TAC and EIR while minimizing the utilization of the diesel generator.

The application of green technologies in the microgrid systems has been extensively studied to improve the performance of a power system and enhance the optimal operation of the traditional power system but the total annual cost and environmental impact reduction index with the utilization of RETs that have not been adequately investigated. This study addresses the abovementioned research gap by presenting fmicon interior-point in the MATLAB environment and RETs to reduce the operation of diesel generator based on the non-linearity of load demand and wind and solar resources. The developed model is capable of maximizing the control variables of RETs and minimizing the control variables of the diesel generator. With the wind and solar data, the optimization model developed in this work is utilized to assess the relationship between the load demand, battery dynamic and local wind and solar resources as well as their effects on the optimal operation of the proposed microgrid system. The comparative analysis is carried out by using some case studies to demonstrate the effectiveness and merits of the proposed technique. The fmincon solver is an accurate optimization tool in the MATLAB environment that has low computational time and allows the users to implement numerous algorithms and solvers as well as provides tangible results within a reasonable time. The highlights of this study are presented as follows:

- Presentation of a methodology that investigates the impact of RERs on a MG system.
- Development of a model that reduces the TAC and EIR and enhances the management of a MG system.
- Reduction of GHG emissions.
- Presentation of a model that optimally controls the flow of power from different sources of a MG system.
- Accomplishment of a sustainable energy that is cost effective.
- Reduction of over dependence on fossil fuel.

The optimal solutions obtained from this study with the utilization of the WTG, PV and ESS show that the proposed method is able to reduce the values of TAC, $C_{fuel,i}$, $C_{emission,i}$, $C_{maint,i}$ and EIR as well as achieving significant cost savings when compared with a base case study where the reciprocating engine is only used to satisfy the same consumer power prerequisites. The output of this research work can be used by the sustainable energy development agencies as inputs to harness the potential of solar resources for strategic planning of the power sector reform and industrial development.

Proposed microgrid system

In this work, a MG system proposed is comprised of the WTG, PV, ESS and diesel generator as presented in Fig. 1.

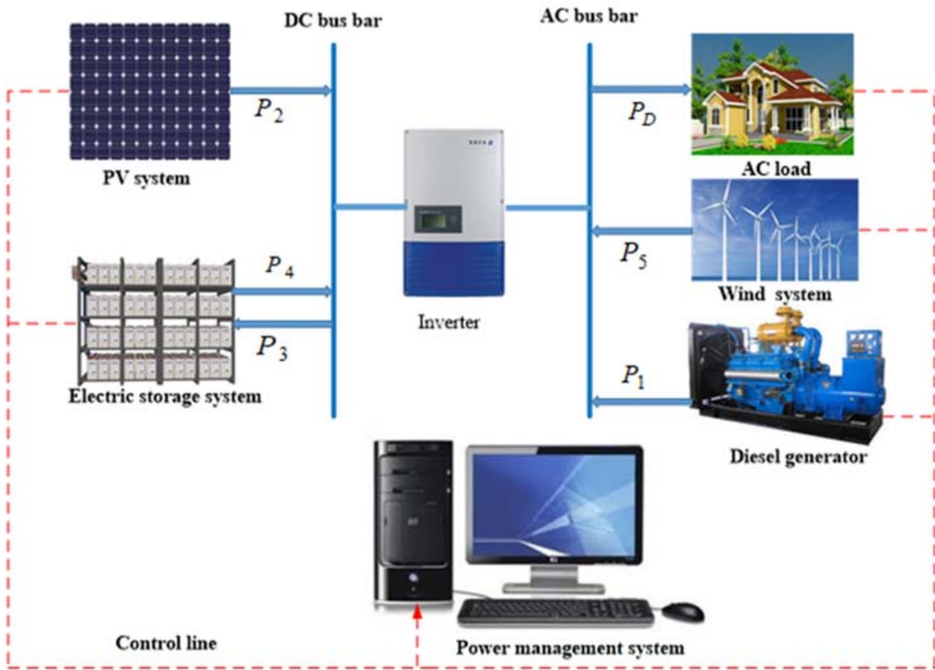


Fig. 1. A PV/wind/battery/diesel MG system

This indicates that consumer power demand is satisfied with the combination of the aforementioned generating units. The ESS is penetrated into the proposed power system to smoothen out the impacts of the stochastic characteristics of local RERs, so that a MG system will have adequate power to meet the consumers' specifications within the operating hours of the generating units. The ESS is utilized in the proposed microgrid system to provide support and backup for the green technologies owing to the stochastic characteristics of solar and wind resources. The excess power from the PV and WTG can be stored by the ESS after the load demand by consumers has been satisfied and released the stored energy into the system wherever there is a shortage of power supply. The ESS is designed not to discharge beyond the minimum permissible limit whenever there is a shortage of power from solar and wind resources. The diesel generator can only be switched on when there is a shortage of power supply from the PV, WTG and ESS. This maximizes the profit merging of the independent power providers (IPPs), reduces load shedding and defers any cost that associated with the expansion of power facilities. The substantial influences of RERs on the TAC and EIR of a MG system can be computed by using the technique proposed in this study. This effect depends on the load profile of a MG system as well as the output power of RERs. The modelling of a MG system is briefly presented as follows:

Diesel generator

A diesel generator that utilizes an electronic control system is used in this study because it senses the changes in the power demand and compensates by regulating the fuel delivery to the reciprocating engine. Most of the diesel generators are designed to operate effectively based on their rated capacities specified by the respective manufacturers while running alone or together with the RERs. The diesel generator can be combined with other RERs in order to enhance the sustainability operation a MG system and at the same time minimize the fuel cost and the quantity of emissions. The operational strategy of the diesel generator with RERs will not only increase the lifetime but also reduce the O&M costs [13]. The total power produced (P_{gen}) by the diesel generator can be assessed by utilizing eq. (1) [7]:

$$P_{gen} = P_n \times N_{gen} \times \eta_{gen} \quad (1)$$

where P_n is the nominal power generated by the diesel generator, $N_{gen}$is the number of the diesel generators and η_{gen} is the efficiency of the diesel generator.

Fuel cost function

The fuel cost (FC) of the diesel generator that carries the largest share of the O&M costs depends on the size and the operating load pattern of the generating unit [13]. The FC of the diesel generator is modelled by using quadratic polynomial methods based on the fuel consumption data and load patterns as expressed in eq. (2) [7].

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

where a, b and c are the cost coefficients of the diesel generator and n and P_i are the number and power generated by the diesel generator.

Wind system

The wind system can operate in conjunction with other RERs and conventional generating units to provide electrical energy for standalone and grid-connected systems. The global acceptance of the wind system for electricity generation has been attributed to technology improvements, economies of scale and financing innovations [1]. The power generated from the wind system is influenced by several factors such as wind spectrum of the site, average wind speed, tower height, wind shear exponent, installing height and swept area of the turbine. [14]. The power output of the WTG is represented by a power performance curve that establishes the relationship between the wind speed and other operating parameters as expressed in eq. (3) [15]:

$$P_{wtg} = \frac{1}{2}C_p v^3 A \eta_g \eta_b \rho \quad (3)$$

where P_{wtg} is the power generated by the WTG (kW), A is the rotor swept area (m^2) of the WTG, ρ is the air density (kg/m^3), v is the wind speed at the hub height (m/s), C_p is the coefficient performance of the WTG, η_b is the gear/bearing efficiency and η_g is the generator efficiency.

PV system

The PV system contains numerous panels that are connected in parallel and series for a reliable power supply at the load centres. The PV system can be configured by the utilities as the off-grid and grid- connected power systems based on the operational requirements, component topologies and the load requirements. The output power of the PV is a function of the solar irradiance, the conversion efficiency of PV panels and ambient temperature. The power generated by the PV panel can be estimated by using eq. (4) [16]:

$$P_{pv} = A_{pv} \times I_{pv} \times \eta_{pv} \quad (4)$$

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

The efficiency of the PV system can be calculated by using eq. (5) [17]:

$$\eta_{pv} = \eta_R \left[1 - 0.9\beta\left(\frac{I_{pv}}{I_{pv,NT}}\right)\left(T_{C,NT} - T_{A,NT}\right) - \beta(T_a - T_r)\right] \quad (5)$$

where η_R is the efficiency of the PV panel that is estimated at reference temperature T_r, β is the temperature coefficient for cell efficiency (typically 0.0004-0.0005/ °C), $I_{pv,NT}$ is the average solar irradiation incident on the PV panel per hour, $T_{C,NT}$ (Typically 45°C) is the cell temperature and $T_{A,NT}$ (20°C) is the ambient temperature at NT test conditions, T_r is the reference cell temperature (typically 25°C) at standard test conditions and T_a is the ambient temperature. NT is the standard and nominal cell operating temperature conditions.

Electric storage system

The stochastic characteristics of RERs coupled with the need to have an uninterrupted power supply at all times with the minimal TAC and EIR have necessitated the integration of the ESS into a MG system. This smoothens out the effects of the intermittent nature of solar and wind resources on the power requirements at the load points [5]. The battery bank can only be charged whenever there is a surplus power from the WTG and PV units. The state of charge (SOC) of the ESS is presented in eq. (6) as [18]:

$$SOC(t) = SOC(0) + \eta_c \sum_{t=1}^{n} P_{ch,i(t)} - \eta_d \sum_{t=1}^{n} P_{dis,i(t)} \quad (6)$$

where η_c *and* η_d are the charging and discharging efficiencies of the battery, $P_{ch,i(t)}$ and $P_{dis,i(t)}$ are the power for charging and discharging the batteries at time.

Objective function

The problem formulation of this research work is based on the minimization of the TAC that consists of $(C_{fuel,i})$, $(C_{emission,i})$, $(C_{cap,i})$ and $(C_{maint,i})$ as well as to reduce the EIR of the emission of the proposed MG subject to satisfaction of the system constraints and consumer load demand. This is achieved by minimizing the operation of the diesel generator and maximizing the operation of RERs in a MG system as presented in Fig. 1. The operational control of a microgrid system that consists of multiple resources is a multi-variable, non-linear and multi-constraint problem where the objective function is achieved with the application of green technologies. The operation of the proposed microgrid system depends on the availability of wind and solar resources, size and type of RETs, load demand and dispatch strategy adopted. The ESS is proposed in the study to be charged by the green technologies only. This indicates that DG is only switched on whenever there is deficiency of power supply to meet the load demand. This design ensures the optimum operation of WTG and PV and the power generated is equal to the load demand. Hence, there is no power wasted when the DG is switched on. The microgrid configuration proposed in this work is to find the optimal scheduled of power generation at given time horizon and optimizes the objective function of the system. The power produce from the proposed microgrid system responds to the load demand based on the constraints and operating limits of the system. The annualized maintenance cost, fuel cost, capital cost and emission cost are taken into consideration in the study, having considered the impacts of above-mentioned components on the optimal operation of power system. The optimization of the aforementioned operating parameters can be presented as follows:

$$F = min \sum_{i=1}^{n} (TAC_i + EIR_i) \quad (7)$$

The first element of the objective function is the total annual cost that is expressed in eq. (8) as:

$$TAC = \left\{ \sum_{i=1}^{n} C_{cap,i} + C_{fuel,i} + C_{maint,i} + C_{emission,i} \right\} \quad (8)$$

The annual emission cost of a MG system can be assessed by utilizing eq. (9) [7].

$$C_{emission,i} = \left\{ \sum_{i=1}^{n} \sum_{j=1}^{m} PF_j \, E_{ij} P \right\} \quad (9)$$

$$= \sum_{i=1}^{m} \sum_{j=1}^{n} PF_j P_i \{ CO_{2,Gi}(t) + SO_{2,Gi}(t) + NO_{x,Gi}(t) \}$$

where PF_j is the externality costs of GHG emissions, P_i is the power output of the diesel generator, m = emission types carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NOx). While E_{ij} is the emission factor of the diesel generator. $CO_{2,Gi}(t)$, $SO_{2,Gi}(t)$ and $NO_{x,Gi}(t)$ are the emissions from the diesel generator source at t^{th} hour. n is the number of the diesel generators. The annual fuel cost of the reciprocating engine can be obtained by using equation (10) [7].

$$C_{fuel,i} = \left\{ \sum_{i=1}^{n} a + bP_i + cP_i^2 \right\} \quad (10)$$

The capital cost happens at the start of a MG project and it can be converted to the annual capital cost with the application of capital recovery factor (CRF) that is presented in eq. (11) as [18] :

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (11)$$

where n is the lifetime of the components that constitute the MG and the interest rate is denoted by i.

The annual capital cost for a MG system can be calculated by using eq. (12).

$$C_{cap,i} = \frac{i(1+i)^n}{(1+i)^n - 1} \left\{ \begin{array}{c} N_{gen} \times C_{gen} + N_{pv} \times C_{pv} \\ +N_{wtg} \times C_{wtg} + N_{ess} \times C_{ess} \\ +N_{inv} \times C_{inv} \end{array} \right\} \quad (12)$$

where N_{gen}, N_{pv}, N_{wtg}, N_{ess} and N_{inv} are the numbers of the diesel generator, PV, WTG, ESS and inverter. While C_{gen}, C_{pv}, C_{wtg}, C_{ess} and C_{inv} are the unit costs of diesel generator, PV, WTG, ESS and inverter.

The annual maintenance cost is one of the most important elements that constitute a MG system occurs during the lifetime of the project. The annual maintenance cost of a MG system can be obtained by using eq. (13).

$$C_{maint,i=}\begin{Bmatrix} N_{gen}\times C_{gen}^{maint}+N_{pv}\times C_{pv}^{maint} \\ +N_{wtg}\times C_{wtg}^{maint}+N_{ess}\times C_{ess}^{maint} \\ +N_{inv}\times C_{inv}^{maint} \end{Bmatrix} \quad (13)$$

where C_{gen}^{maint}, C_{pv}^{maint}, C_{wtg}^{maint}, C_{ess}^{maint} and C_{inv}^{maint} are the annual maintenance costs for the diesel generator, PV, WTG, ESS and inverter.

The second element of the objective function is the EIR for GHG emissions such as CO_2, NO_x and SO_2 for the MG system. It is considered in this paper to reduce the aforementioned GHG emissions. The second part of the objective function can be used to assess the environmental benefits of using the PV and WTG in a MG system. The mathematical formulation of this objective function is given below [3]:

$$EIR_i=\frac{PE_{i/wRERs}}{PE_{i/woRERs}} \quad (14)$$

$PE_{i/wRERs}$ is the amount of GHG emissions with the application of RERs.

$$PE_{i/wRERs}=\sum_{i=1}^{n}x_i y_{ii} \quad (15)$$

$PE_{i/woRERs}$ is the amount of GHG emissions without the application of RERs.

$$PE_{i/owRERs}=\sum_{i=1}^{n}x_k y_{ik} \quad (16)$$

where x_i is the power generated by the diesel generator with RERs, y_{ii} is the quantity of the emission of the ith pollutant of the diesel generator, x_k is the power generated by the diesel generator without RERs andy_{ik} is the quantity of the emission of the kth pollutant of the diesel generator.

The multi-objective function is subject to the following constraints:

i. The power system balance limits

The power requirements of the consumers are satisfied when the RERs, ESS and diesel generator operate within the allowable limits of a MG system. The total power generated from different components of the proposed microgrid system must be equal to the power demand at time t. The operation of a MG system is restricted based on the constraint presented in equation (17) as:

$$\sum_{i=1}^{n}P_{1,,i(t)}+\sum_{i=1}^{n}P_{2,,i(t)}-\sum_{i=1}^{n}P_{3,,i(t)}+\sum_{i=1}^{n}P_{4,,i(t)}+\sum_{i=1}^{n}P_{5,,i(t)}=\sum_{i=1}^{n}P_{D,,i(t)} \quad (17)$$

where $P_{1,i(t)}$, $P_{2,i(t)}$ *and* $P_{5,i(t)}$ are the power produced by the diesel generator, PV and WTG. $P_{3,i(t)}$ is the power for charging the battery and $P_{4,i(t)}$ is the power discharged by the battery. $P_{D,i(t)}$ is the power demand by the consumers as presented in Fig. 1.

ii. The generating power output constraints

The WTG, PV, ESS and diesel generator are structured to operate within the optimal limits specified by the manufacturer of each unit. The aforementioned generating units are modelled as variables controllable power sources that range from minimum to their maximum power limits at any time t. The variable limits utilized in this work are the output power of WTG, PV, ESS and DG at 24 hours horizon. The minimum and maximum limits of the aforementioned generating units depend on the features of the RERs, ESS and diesel generator. The power output of each generating can be expressed as:

$$\begin{cases} P_{1,i(t)}^{min} \leq P_{1,i(t)} \leq P_{1,i(t)}^{max} \\ P_{2,i(t)}^{max}, P_{2,i(t)}^{min} \leq P_{2,i(t)} \\ P_{3,i(t)}^{min} \leq P_{3,i(t)} \leq P_{3,i(t)}^{max} \\ P_{4,i(t)}^{min} \leq P_{4,i(t)} \leq P_{4,i(t)}^{max} \\ P_{5,i(t)}^{min} \leq P_{5,i(t)} \leq P_{5,i(t)}^{max} \end{cases} \tag{18}$$

iii. Constraints of electric storage system

The operation of the ESS is a function of the discharge and charge constraints based on the availability of solar and wind resources and the depth of discharge (DOD). The ESS is structured to operate between the minimum and maximum allowable limits of the SOC expressed in eq. (19) as [18]:

$$SOC^{min} \leq \left\{ SOC(0) + \eta_c \sum_{t=i}^{n} P_{3,(t)} - \eta_d \sum_{t=i}^{n} P_{4,(t)} \right\} \leq SOC^{max} \tag{19}$$

$$SOC^{min} \leq SOC \leq SOC^{max} \tag{20}$$

$$SOC^{min} = (1 - DOD)SOC^{max} \tag{21}$$

Optimization technique

One of the benefits of incorporating the PV and WTG into a MG system is the generation of power at the minimum $(C_{fuel,i})$, $(C_{emission,i})$, $(C_{maint,i})$ and EIR when compared with utilizing the reciprocating engine alone to serve the same load requirements. This study investigates the environmental and economic impacts of sustainable energy technologies on a power system. The model that provides an optimal solution for minimization of the operating costs is presented in this study based on the operational strategies of the PV, WTG, ESS and diesel generator system. The objective of this work is based on the development of a model that can be used to minimize the TAC and EIR, having considered the operation scheduled of the diesel generator. Fmincon is a state-of-the-art optimization technique that has the ability to solve medium to large scale problems quickly and supplies Hessian information. The objective function of this study can be accomplished by using the fmincon solver that is presented in equation (22):

$$F = min \sum_{i=1}^{n} f(x) \quad (22)$$

$$\min f(x) \; such \; that \begin{cases} C(x) \leq 0 \\ C_{eq}(x) = 0 \\ A.x \leq b \\ A_{eq}.x = b_{eq} \\ lb \leq x \leq ub \end{cases} \quad (23)$$

where C(x) and Ceq (x) are functions that return vectors, x, b, b_{eq}, lb and ub are vectors, A and A_{eq} are matrices, f(x) is a function that returns a scalar, f(x), C(x) and C_{eq} (x) are non-linear functions and lb and ub are lower and upper bounds.
The output power of different generating sources in a MG system can be expressed by the variable function x, which is presented in equation (24). The code can be developed in the MATLAB environment by utilizing x variables. The power function to be evaluated must be partitioned into small equal intervals (*N*) with a sampling time (*Δt)*.

$$\begin{aligned} P_1 &= x(1{:}N) &&= [x_1 \;\; x_2] \\ P_2 &= x(N+1{:}2N) &&= [x_3 \;\; x_4] \\ P_3 &= x(2N+1{:}3N) &&= [x_5 \;\; x_6] \\ P_4 &= x(3N+1{:}4N) &&= [x_7 \;\; x_8] \\ P_5 &= x(4N+1{:}5N) &&= [x_9 \;\; x_{10}] \end{aligned} \quad (24)$$

The power balance of the multiple sources can be subdivided into two sampling intervals and presented in equations (25-26) as:

$$N = 1 \rightarrow x_1 + x_3 + x_5 + x_7 + x_9 = P_{D1} \quad (25)$$

$$N = 2 \rightarrow x_2 + x_4 + x_6 + x_8 + x_{10} = P_{D1} \quad (26)$$

The variable function x presented in equations (25-26) can be converted into the matrix form by using the following steps:

$$\begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ . \\ . \\ . \\ . \\ . \\ x_{10} \end{bmatrix} = \begin{bmatrix} P_{D1} \\ P_{D2} \end{bmatrix} \quad (27)$$

Battery dynamics

The dynamic performance of batteries depends on the SOC, temperature, design parameters, battery performance, lifetime, etc. The relationship between the control variables and the state variables of a MG system can be established by using the battery dynamics presented in eq. (28) as:

$$
\begin{cases}
SOC(0) + \eta_c \sum_{i=1}^{j} P_{3(j)} - \eta_d \sum_{i=1}^{j} P_{4(j)} \leq SOC^{max} \\
\eta_c \sum_{i=1}^{j} P_{3(j)} - \eta_d \sum_{i=1}^{j} P_{4(j)} \leq SOC^{max} - SOC(0) \\
SOC^{min} \leq SOC(0) + \eta_c \sum_{i=1}^{j} P_{3(j)} - \eta_d \sum_{i=1}^{j} P_{4(j)} \\
-\eta_c \sum_{i=1}^{j} P_{3(j)} + \eta_d \sum_{i=1}^{j} P_{4(j)} \leq SOC(0) - SOC^{min}
\end{cases}
\tag{28}
$$

Technical specifications

The objective of this paper is accomplished by utilizing the technical specifications of all the components of the proposed MG system as presented in Table 1. The proposed methodology is used for the provision of the optimal power solution that serves some loads in De Aar, a community in South Africa.

Table 1 Technical data sheet [18-22]

Description	Diesel generator	Wind turbine generator	PV	Battery
Installed capacity	2X18= 36 kW	10 kW	22 kW	2 kW
Manufactures/ Model number	Cummins/ DNAC	Aircon/ HAWT	SolarWorld Sunmodule/ SW 250	BSB/ Solar 12-250
Capital cost	1521 $/kW	651$/kW	550 $/kW	651 $/kW
Lifetime	25000h	25 yr	25 yr	5 yr
Mainten-ance cost	0.01258 $/kWh	20 $/kW/yr	10 $/kW/yr	10 $/unit/yr
Other operating paramet-ers	Cost coefficient: a= 0.4333, b= 0.2333, c = 0.0074, Random voltage variation = ± 1% and Random frequency variation = ± 0.25%	v_{ci}=2.5 m/s, v_r=11 m/s, v_{co} =32 m/s, number of blades = 3 and blade swept area = 39.6 m^2	Voc = 37.8 V, Ta = 30 °C, NOCT =46 °C, I_{sc} = 8.28A, V_{mp} = 31.1V, I_{mp} = 8.05A, K_v = 0.30%/k, K_i = 0.004%/k and operating temp. = -40°C -85°C	Operating temp. = -15ºC to 60ºC, Battery max SOC= 95%, Battery min SOC= 40%, Battery discharging efficiency = 100% and Battery charge efficiency = 85%

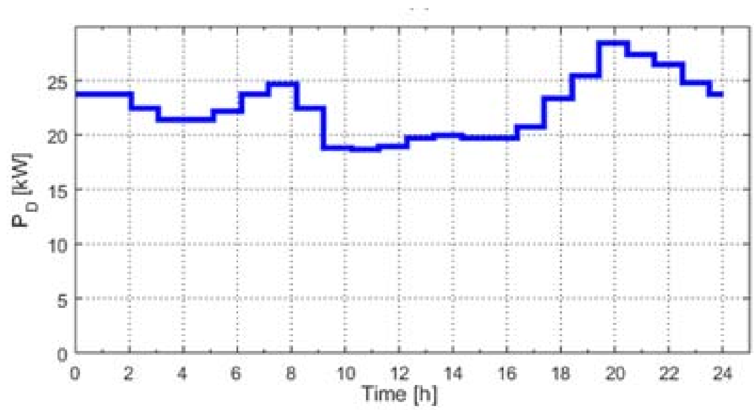
Results and discussions

The operation of different case studies that are used in this study depends on the relationship between the power supply from the generating units and the power demand. The environmental and economic influences of the PV and WTG in a power system are assessed by considering the listed case studies:

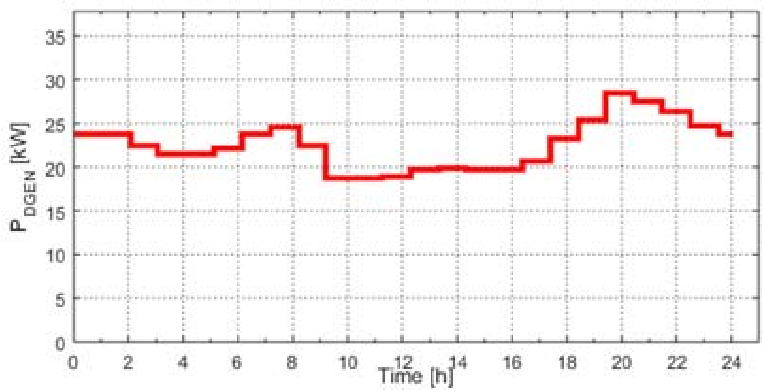
(i) Case study 1: Diesel generator alone.
(ii) Case study 2: PV system and diesel generator.
(iii) Case study 3: WTG system and diesel generator.
(iv) Case study 4: WTG system, PV system and ESS and diesel generator respectively.

The discussions and results obtained from four case studies are presented as follows:

Case study 1: This demonstrates a condition where the power is provided by means of just diesel generator without the utilization of the WTG, PV and ESS. The total variation of the typical daily load profile of the consumer power demand and power generated by the diesel generator are shown in Fig. 2 (a-b). It can be seen in Fig. 2b that the operation of diesel generator has been stressed due to the fact that it is producing 100% of the entire load. Moreover, the results obtained from this scenario as shown in Table 2 demonstrate that the values of the TAC, $(C_{fuel,i})$, $(C_{emission,i})$ and $(C_{maint,i})$ are very high since the diesel generator is not a renewable energy source. The comparison of various costs of the case studies is presented in Fig. 3a. The total annual cost obtained in this case study is \$135000/yr, with the breakdown presented in Fig. 4a while the quantity of fuel consumption is 106000 L/yr. Moreover, the quantity of gas emitted into the atmosphere as presented in Table 2 shows that CO_2 has the largest percentage of the GHG emissions among the three pollutants. This indicates that CO_2 is the main causes of GHG effects with the amount of 32800 kg/yr. It demonstrates that case study 1 has the highest emission and the value of an EIR that is estimated to be 1, inferable from the way that the diesel generator operates alone without the utilization of the PV, WTG and ESS. The simulated results obtained from this scenario indicate that the operation of the diesel generator alone is very expensive and environmentally unfriendly due to high fuel and maintenance costs and the large quantity of GHG emissions.



(a)



(b)

Fig. 2 **(a).** Power demand and **(b)** Power output of the diesel generator.

Table 2 Comparison of costs and emissions of the case studies

Case studies	Case study 1	Case study 2	Case study 3	Case study 4
TAC ($/yr)	135000	113000	98900	83600
Fuel cost($/yr)	83700	65200	55800	43700
Capital cost ($/yr)	21100	22500	21500	23100
Maintenance cost ($/yr)	24900	19800	18100	14100
Emission cost ($/yr)	4880	3800	3500	2650
Quantity of fuel (L/yr)	106000	82500	70600	55300
Quantity of CO_2 (kg/yr)	32800	25600	23600	17900
Quantity of Nox (kg/yr)	1330	1030	951	722
Quantity of SO_2 (kg/yr)	71.27	56	51.12	38.8
EIR	1	0.78	0.72	0.54

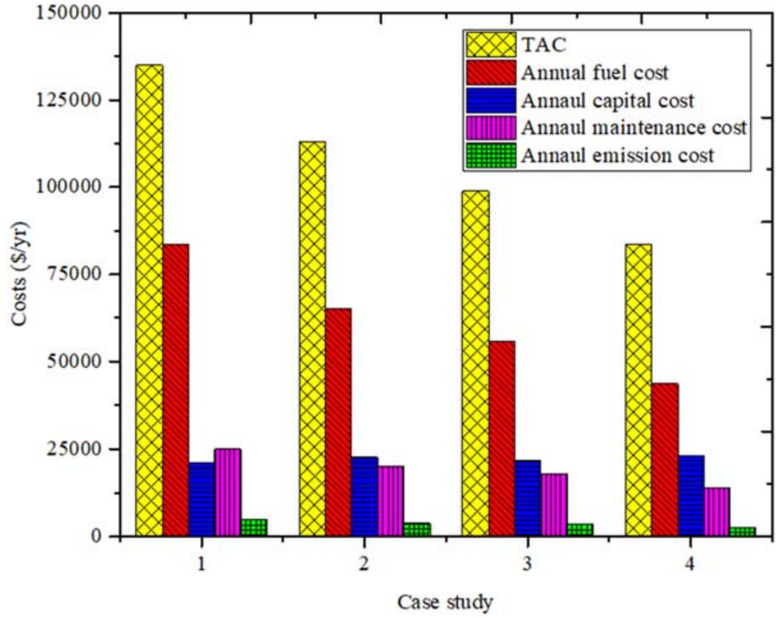


Fig. 3a. Total annual costs of the system.

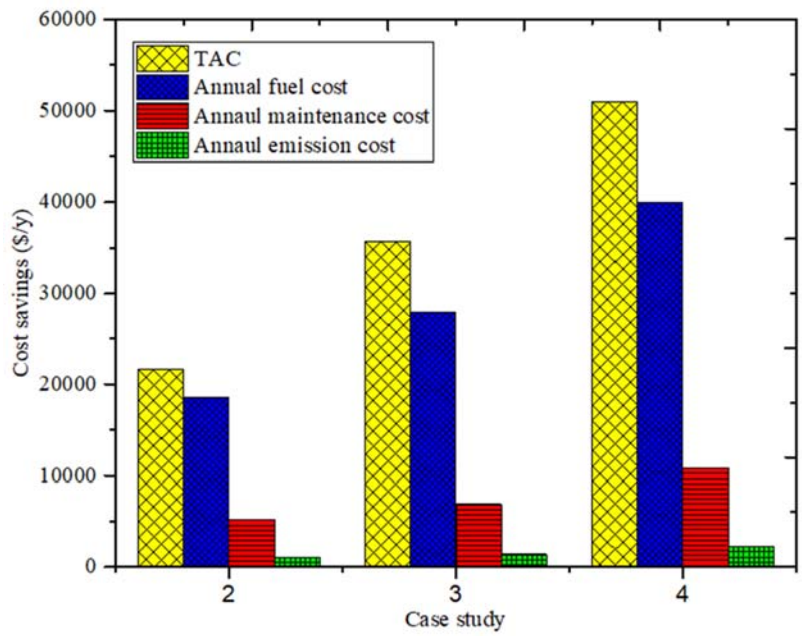


Fig. 3b. Cost savings of the system.

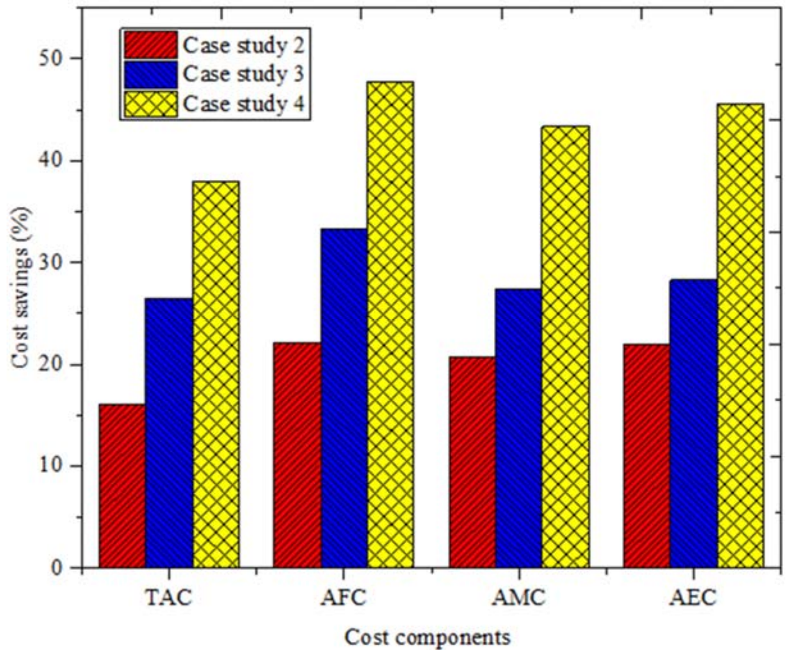


Fig. 3c. Percentage cost savings of the system (where AFC, AMC and AEC are annual fuel cost, annual maintenance cost and annual emission cost).

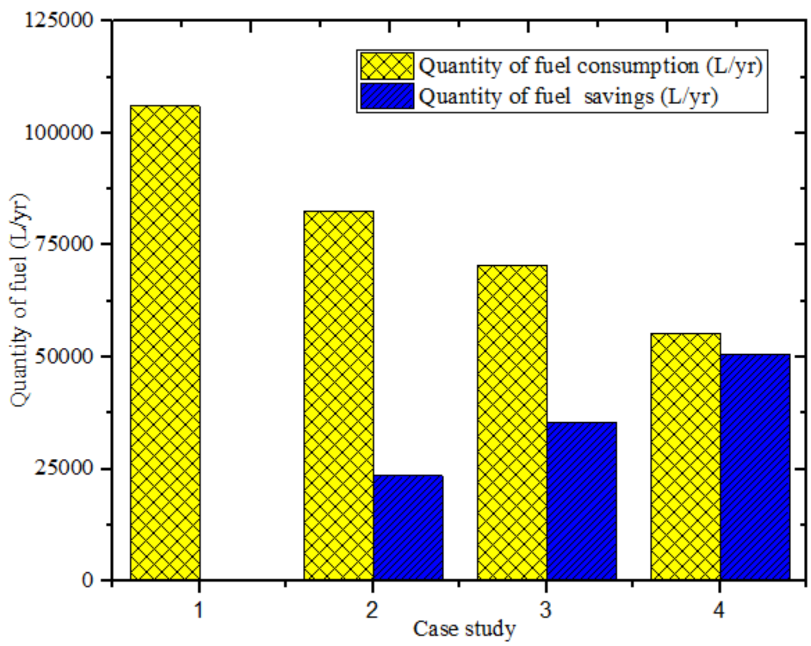
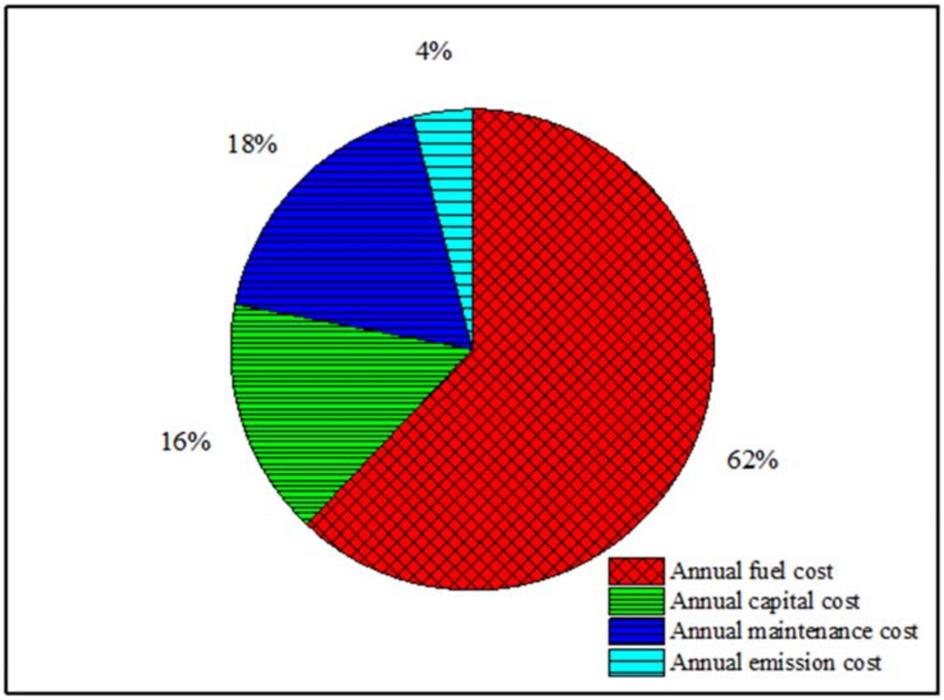
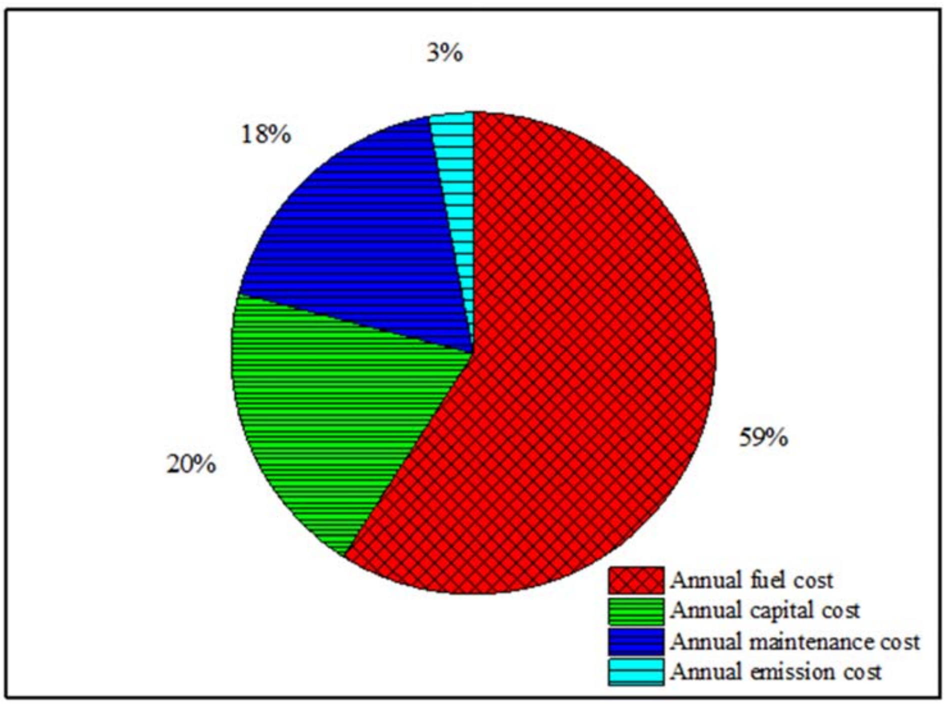


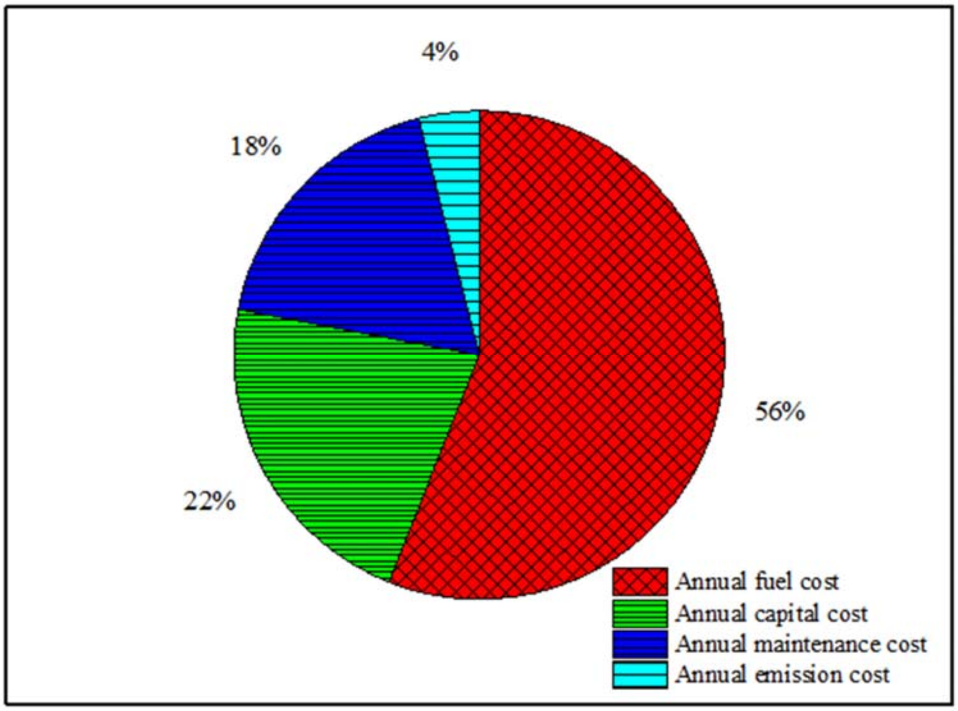
Fig. 3d. Quantity of fuel consumption for each case study.


4%
18%
16%
62%
Annual fuel cost
Annual capital cost
Annual maintenance cost
Annual emission cost

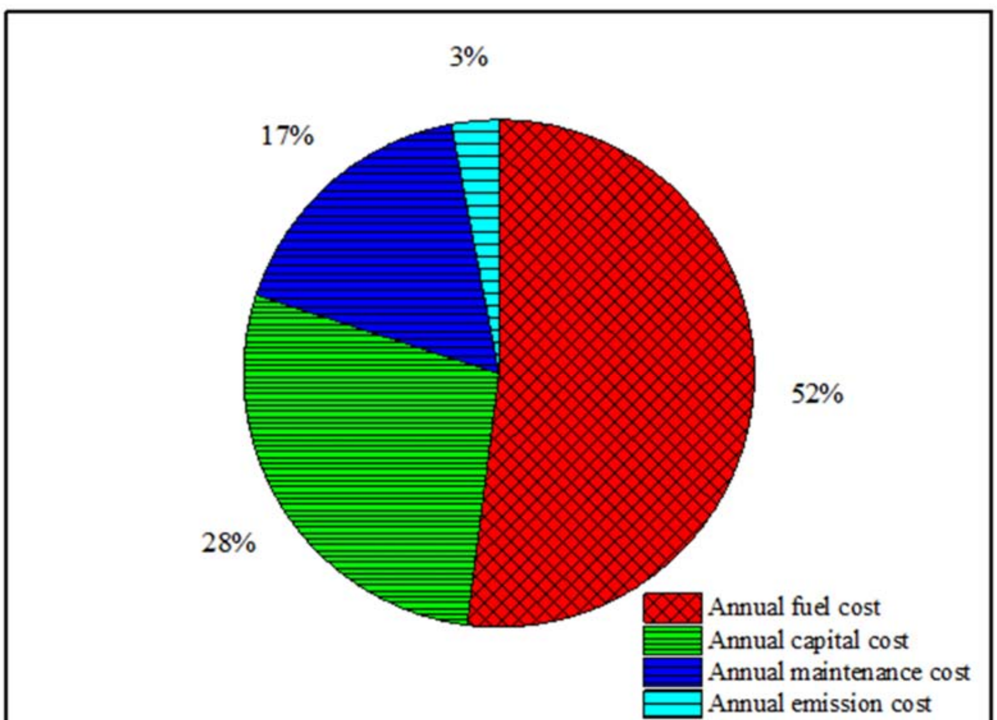
(a)


3%
18%
20%
59%
Annual fuel cost
Annual capital cost
Annual maintenance cost
Annual emission cost

(b)



(c)



(d)

Fig. 4. Breakdown of the total annual cost for **(a)** Case study 1, **(b)** Case study 2, **(c)** Case study 3 and **(d)** Case study 4.

Case study 2: The second case study utilizes a combined operation of the diesel generator and PV to reduce the TAC, $(C_{fuel,i})$, $(C_{emission,i})$ and $(C_{maint,i})$ as well as the EIR of emissions. The power contributed by each component of a MG system in this scenario is shown in Fig. 5 (a-c). The utilization of the PV has minimized the operation of the diesel generator as presented in Fig. 5b. This shows that the application of the PV has reduced the power produced from the diesel generator by more than 40% when compared with Fig 2b. The values of the operating costs as presented in Table 2 and Fig. 3a have confirmed the impacts of the PV in a MG system. Moreover, the utilization of the PV in a MG has improved the cost savings of the TAC, $(C_{fuel,i})$, $(C_{maint,i})$ *and* $(C_{emission,i})$ by 21.6 k\$/yr, 18.548 k\$/yr, 5.164 k\$/yr and 1.0742 k\$/yr as shown in Fig. 3b and Table 3. The simulated results obtained from case study 2 prove that application of the PV in a MG system has enhanced the cost savings owing to the results presented in Fig. 3c. In addition to this, the amount of fuel consumption in this case study is 82500 L/yr as shown in Fig. 3d, this signifies that 23480 L/yr has been saved when compared with the base case study. The total annual cost obtained in this case study is \$113000/yr, with the breakdown presented in Fig. 4b. The application of PV also has a significant impact on the quantity of GHG emissions that emanate from the diesel generator. The quantity of the emissions from a MG system has been significantly reduced by CO_2 = 7236 kg/yr, NOx = 292. 2 kg/yr and SO_2 = 15.70 kg/yr. The value of EIR obtained in this case study is 0.78. This shows that the integration of the PV into a MG system has established that it is environmentally and economically viable in terms of the TAC and EIR when compared with the case study 1.

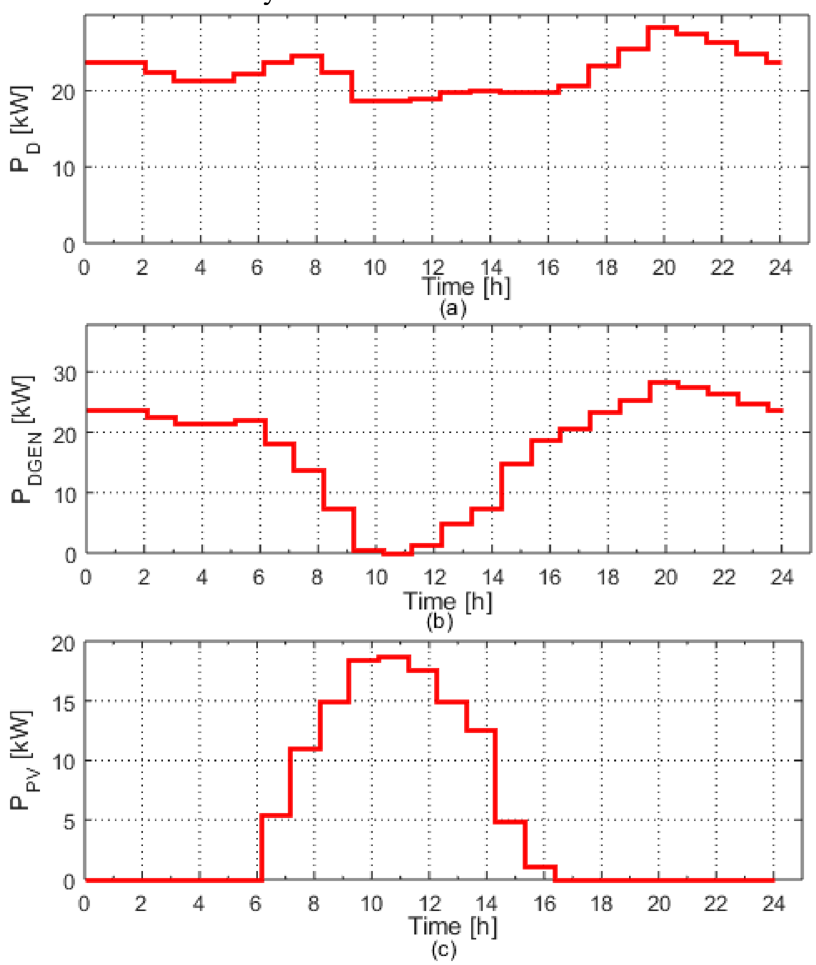


Fig. 5. **(a)** Power demand, **(b)** power output of the diesel generator and **(c)** PV system.

Table 3 Cost savings and quantity of emission and fuel reduction for the case studies

Case studies	Case study 2	Case study 3	Case study 4
TAC ($/yr)	21600	35696	50994
Fuel cost($/yr)	18548	27924	40034
Maintenance cost ($/yr)	5164	6852	10815
Emission cost ($/yr)	1074.2	1378.9	2222.3
Quantity of fuel (L/yr)	23480	35348	50678
Quantity of CO_2 (kg/yr)	7236	9288	14969
Quantity of Nox (kg/yr)	292.2	375.07	604.48
Quantity of SO_2 (kg/yr)	15.70	20.152	32.48

Case study 3: The third case study contains the WTG and a diesel generator for investigation of the environmental and economic impacts of the WTG in a MG system. The power output of each constituent of the system is presented in Fig. 6 (a-c). The utilization of the WTG has reduced the power generated by the reciprocating engine and increased the reserve margin of a MG system. This establishes that the application of the WTG has reduced the power produced by the diesel generator by less than 50% of the installed capacity and minimized the stress on its operation when compared with Fig. 2a. It can be validated in Table 2 and Fig. 3a that the values of the key operating parameters have been reduced substantially with the incorporation of the WTG system into the existing power system. The potential of the wind resources has enhanced the cost savings of the TAC, $(C_{fuel,i})$, $(C_{maint,i})$ and $(C_{emission,i})$ of a MG system by 35.696 k$/yr, 27.924 k$/yr, 6.852 k$/yr and 1.3789 k$/yr in Fig. 3b. The percentage of the cost savings with the utilization of the WTG in the proposed MG system is presented in Fig. 3c. The fuel consumption in this case study is 70600 L/yr as shown in Fig. 3d, this shows that 35348 L/yr has been saved based on the comparison with the base case study. The total annual cost obtained in this case study is $98900/yr, with the breakdown presented in Fig. 4c. The utilization of the WTG in case study 3 has also reduced the emissions of the diesel generator as presented in Table 3. This has established the fact that the quantity of emissions from the diesel generator has been reduced by CO_2 = 9288 kg/yr, NOx = 375.07 kg/yr and SO_2 = 20.15 kg/yr, mainly due to the application of the WTG. The value of EIR in this scenario has been further reduced to 0.72.

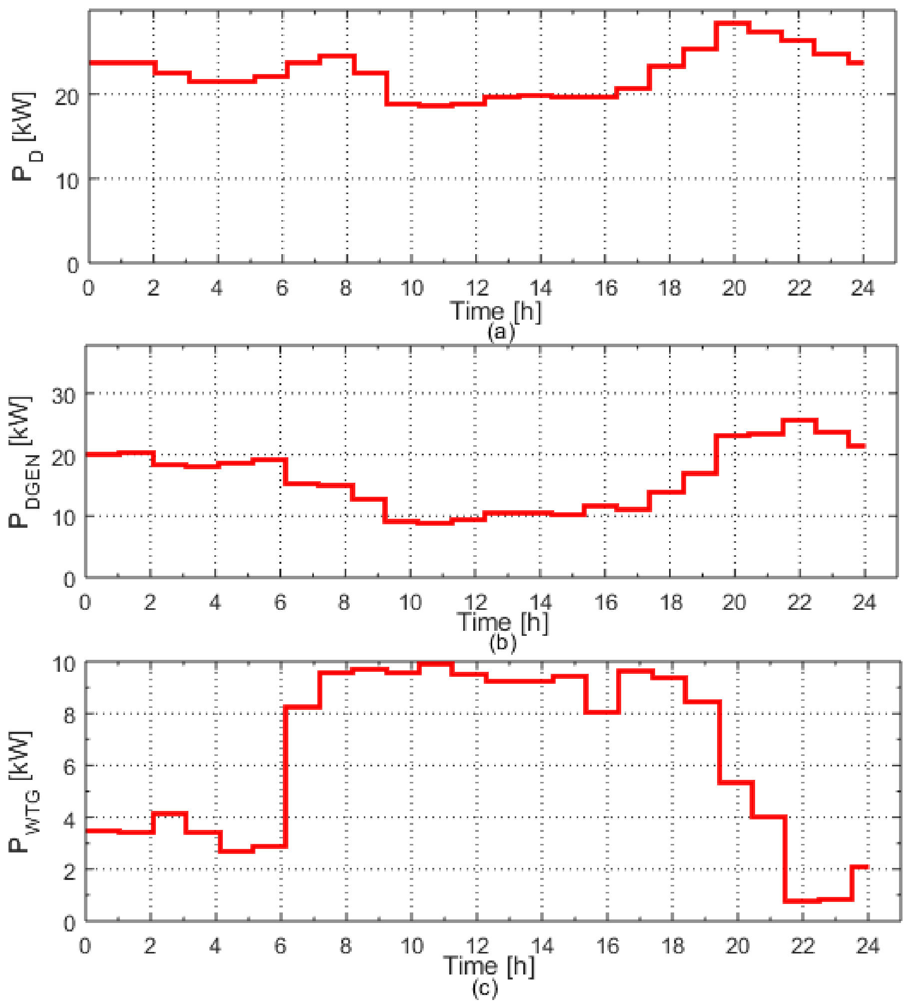


Fig. 6. **(a)** Power demand, **(b)** power output of the diesel generator and **(c)** WTG system.

Case study 4: In the case study 4, the load demand is met with the operation of the diesel generator in conjunction with the PV, WTG and ESS as shown in Fig. 7 (a-f). A MG system is running properly based on the power supply from the aforementioned generating units. The operation of the reciprocating engine has been reduced substantially with the utilization of the PV, WTG and ESS when compared Fig. 2a and Fig. 7 (a-d). The operation of the diesel generator is switched-off completely between the 8 to 14 hours of the day due to the potential of solar and wind resources. As a result of this, the fuel cost that carries the largest share of the O&M costs of a MG system, as well as other operating parameters have been minimized considerably as presented in Table 2 and Fig. 3a. Moreover, the results obtained in the case study 4 indicate that the cost savings of the TAC, $\left(C_{fuel,i}\right)$, $\left(C_{maint,i}\right)$ and $\left(C_{emission,i}\right)$ have increased tremendously by 50.994 k$/yr, 40.034.63 k$/yr, 10.815.7 k$/yr and 2.2223 k$/y as presented in Fig. 3b and Table 3. This demonstrates that more costs are saved with the combination of the PV, WTG, ESS and diesel generator in a MG system as presented in Fig. 3c. The utilization of RERs and ESS in a MG system also has a great impact on the quantity of fuel consumption by reducing its value to 55300 L/yr as presented in Fig. 3d. The quantity of fuel saved in this case study is 50678 L/yr when compared with the case study 1. Based on the methodology applied in this work, the total annual cost obtained in this case study is $83600/yr, with the breakdown presented in Fig. 4d. The quantity of NOx, CO_2 and SO_2 emissions from a MG system is also reduced as presented in Table 2. This is primarily

attributed to the fact that the quantity of emissions from the diesel generator is reduced to the optimal level, due to the availability of the local wind and solar resources that can be utilized to generate electric power from the PV and WTG systems. The effects of RERs on the power system are noticeable on the amount of CO_2, NOx and SO_2 emissions that have been reduced by 14969 kg/yr, 604.4847 kg/yr and 32.4783 kg/yr respectively.
The value of EIR obtained in this case study is estimated to be 0.54. This has justified that the quantity of emissions from the diesel generator has been reduced extensively. The application of the PV, WTG and ESS has reduced the operating costs of a MG system. Having compared the results obtained in the four case studies, it is validated that an increase in the number of RERs and ESS has reduced the values of TAC, $(C_{fuel,i})$, $(C_{maint,i})$, $(C_{emission,i})$ and EIR significantly. Hence, the results obtained in this case study are environmentally and economically are viable when compared with other case studies. This is mainly due to the potential of the local solar and wind resources that are available in the site and combined operation with ESS.

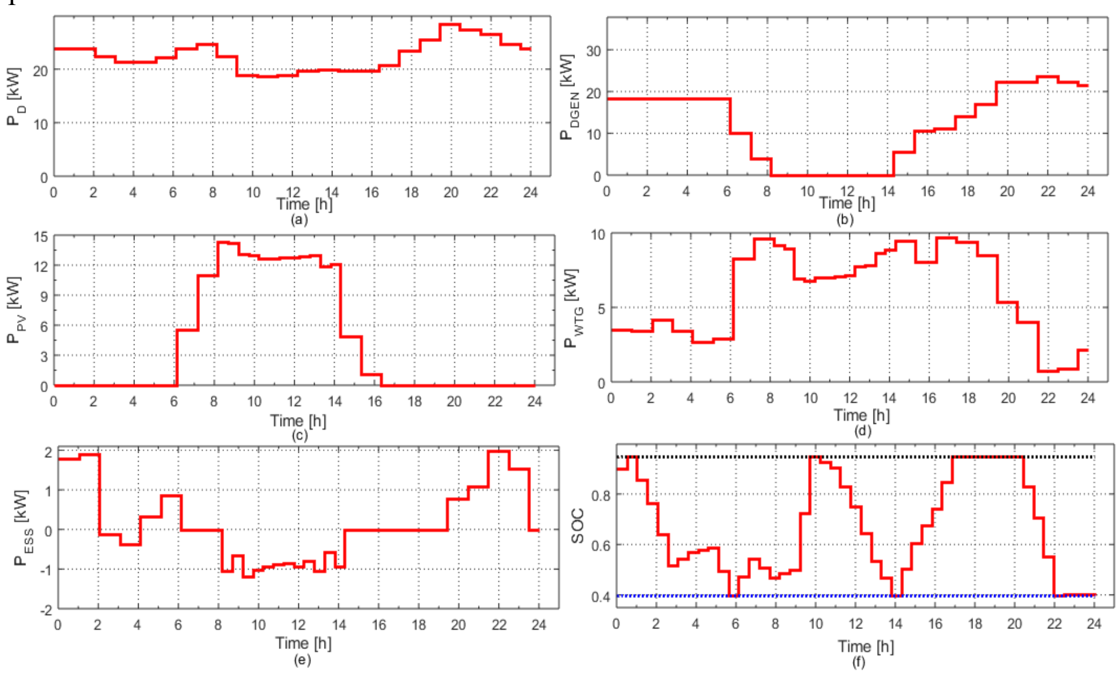


Fig. 7. **(a)** Power demand, **(b)** power output of the diesel generator, **(c)** PV system, **(d)** WTG system, **(e)** ESS and **(f)** SOC of the battery.

Conclusion

This research work has presented a methodology that reduce the values of the total annual cost, annual fuel cost, annual maintenance cost, annual capital cost and annual emission cost with the incorporation of PV, WTG and ESS into a MG system. The results obtained from this work have proved that economic and environmental challenges that several countries are facing due to over reliance on the fossil fuels as the primary source of power generation can be solved with the utilization of RERs. This study indicates that the integration of RERs into a MG system can reduce the total annual cost and EIR as well as achieve a significant cost savings. This is justified by comparing the results obtained from several case studies in this research work. It can be validated from the outcomes of the research that the embedded operation of the diesel generator with other RERs in a MG system accomplished a better fuel and O&M cost savings and emission reduction rather than utilizing a diesel generator alone to supply a similar load demand. The objective function used in this paper will assist the network operators to make the best choices when confronting various financial and technical challenges. The results presented in this paper have provided important information that can be used by the utilities for a suitable operation of their power systems. Hence the outcomes of this research work can be used as benchmarks to improve the economic development in emerging economies and reduce over 1.1 billion people on the global note that do not have access to power supply owing to financial, technical and topography constraints. The power solutions provided by RERs are vital for achieving universal access to electricity based on an enabling environment created by the government and international organisations with the right policies, strategic planning, regulations and incentives. Owing to the aforementioned information, there is a cordial relationship between economic growth and access to electricity. The technique proposed in this work can be utilized to solve numerous problems that associated with the economic operation of a microgrid system.

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