

Technical, economic, and environmental assessment of the distribution power system with the application of renewable energy technologies

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Abstract: Renewable energy technologies (RETs) have been universally accepted as the prospective choice to increase the reliability of the power system and to reduce the effects of emission cost (EC), fuel cost (FC), maintenance cost (MC), power loss (PL), total annual cost (TAC) and voltage deviation (VD) on the operation of the power system. The above-mentioned performance indicators are used in the study to assess the effects of diesel generator (DG), electric storage system (ESS), photovoltaic (PV), and wind turbine generator (WTG) on the environmental, economic, and technical performance of a microgrid system with the utilization of modified Roy Billiton Test System (RBTS) bus 4 distribution network. The proposed model is utilized to achieve the goals of the study by minimizing the costs that are identified with the power outages, TAC, MC, EC, FC, PL, and VD of the system with the application of an intelligent optimal control method based on the fmincon solver. The outcomes of the study can be used as benchmarks to assess the cost-effectiveness of increasing the capacity of universal power supply and resolve the universal power crisis owing to the depletion of fossil fuels. The study provides vital information to enhance the efficiency of the power system and the guidelines to promote the development of sustainable energy.

Keywords: Emission cost; microgrid system; photovoltaic; reliability; renewable energy technologies; wind turbine generator

1. Introduction

The sudden increase in the power consumption at minimum power outages coupled with the universal acceptance of RETs as the potential alternative for rural electrification projects has encouraged many MGOs to incorporate PV and WTG into their power systems [1]. This will increase the reliability of the system and improve the quality and efficiency of power supply at the load points [2]. The substantial increase in the demand of RETs to meet the global power requirements has been attributed to depletion of fossil fuel, instability of fossil fuel prices, soil degradation, public health hazards, ozone layer depletion and global warming as well as acid rain

pollutants that have increased considerably owing to the high rate of fossil fuel consumption [3], [4]. The high pressure on the utilization of the fossil fuel has forced many government agencies to spend millions of dollars annually on the subsidies or incentives for the imported petroleum products. Presently, many countries in the world have made concerted efforts to accomplish a high level of RETs integration into their power systems with the utilization of financial schemes such as carbon tax, tax holiday, subsidies, renewable energy investment incentives, low import duty for the components of RETs, low interest rate loan and other financing programs from the private sector [5]. Most of the supporting policies are initiated by government and international organizations as a measure to encourage the application of low carbon intensive energy resources for the generation of electricity for commercial, industrial and residential applications. Owing to the persistent efforts made by different organizations to improve energy efficiency and access to electricity, many countries have agreed to meet the projections of the Paris agreement on sustainable energy development. The incorporation of RETs into the distribution network improves the overall performance and the reliability of the power system, reduces investment that is required for rural electrification projects owing to economics of scale, reduces additional costs that are associated with spinning reserve stations, improves power supply quality and provides auxiliary grid supports [6]. Moreover, it minimizes the power outages, bus voltage deviation and power losses as well as defers the costs that relate to the massive extension of utility power networks to rural communities.

The high demand of electricity occasioned by industrialization, population growth and universal financial extension has attracted public attention, owing to the delivery of an uninterrupted power supply at the load centres [7]. As a matter of fact, uninterrupted power supply has consistently been significant on account of the financial growth and social prosperity of a country. Moreover, the economic status of a country is a function of availability of uninterrupted power supply at respective load points since most of the industrial and commercial sectors rely on the capacity of the power generated to improve their activities [8]. The reliability assessment is one of the important tools for the modernization and planning of the power system. The recent proliferation of the distribution network with a number of RETs, battery system, electric vehicle and conventional generating units have contributed tremendously in one way to another to the improvement of the power system performance [9]. The reliability of power supply can be measured by using the economic impacts of power interruption on customers and DNOs based on the fault conditions of the power system. Therefore, specific benchmarks and penalties are introduced by the regulators as a measure to increase the level of the reliability in the course of planning and designing a power system. The evolution of the traditional power systems towards the smart grid systems and development of sustainable energy has produced significant opportunities to further increase the reliability of power supply. The WTG, PV and ESS are used in this paper to reduce the economic losses that are related to the customer interruptions, voltage variation and power loss as well as reduction of the duration and frequency of power outages. For this reason, RETs play a prominent role in the availability of uninterrupted electricity at the load centres [10]. Conversely, due to the intermittent nature of wind and solar resources that can

cause unpredictable power supply at the load centres; it is a great challenge to design a reliable power system that operates with only RETs. The fluctuation of local renewable energy resources can be mitigated with the utilization of ESS so that it will minimize the power restoration time and the associated power outage costs. This problem can also be overcome by utilizing a microgrid system that utilizes different configurations and operates with the multiple energy sources.

The MGOs, DNOs, performance analyzers and power sector decision makers can utilize RETs to increase the reliability and minimize the emission cost, operating costs, V_D and P_L of the microgrid systems. The modern distribution power system is designed with the smart grid features that allow it to operate effectively during a faulty operation so that both RETs and ESS can provide power to the interrupted sections of the networks that cannot be supplied from the utilities. The application of RETs in the traditional network reduces the time response needed for power system restoration during the fault conditions, decreases the peak load demand from the utility and improves the security of power supply under emergency conditions [11]. In view of this, the impacts of RETs on the technical, economic and environmental benefits will be duly addressed as a measure to support the global planning of the power system and to make appropriate technical decisions that can optimize the operations of the distribution networks. This research work studies the effects of RETs on the performance of a power by using various energy compositions based on the TAC, TOC, P_L , V_D , RI and EIR. The distribution power system plays a prominent role in provision of electrical power supply at the load centres; however the voltage variation and power loss have been reported to be very high owing to some technical issues. The power loss and voltage profile of the distribution power system can be optimized by using the following techniques: increasing operating voltage, distributed energy technologies, increasing the cross section area of the cable, compensating reactive power and balancing loads. Owing to the technical, environmental and economic benefits of distributed energy resources, RETs is used in the study to reduce the power loss and improve the voltage profile of the system while satisfying operation constraints. A few research works have been done on the global note with the utilization of RETs for the optimization of standalone and grid-connected microgrid systems. Some of the microgrid/hybrid/smart energy systems with their configurations, technical parameters, methodology, performance indicators, power generating units and performance measures as found in other research works are presented in Table 1.

Table 1 A literature review of standalone and grid-connected microgrid systems

Architecture of the power system	DG	FC	PV	WTG	MT	BAT	Biogas	EV	HP	Methodology	Performance indicators
Standalone/grid connected system [12]	✓	×	✓	✓	×	✓	×	×	×	HOMER	COE, CO ₂ emission, NPC and RF
A smartgrid system[13]	✓	✓	✓	✓	✓	✓	×	×	×	MOPSO	Emissions and OC
Standalone system [14]	✓	×	✓	✓	×	✓	✓	×	×	HOMER	COE, NPC, O&M costs and RF
Grid-connected HES [15]	×	×	✓	✓	×	×	×	×	×	GA	CEPs and LCC
HES [16]	✓	×	✓	✓	×	✓	×	×	×	TC	AE
HES [17]	✓	×	✓	×	×	✓	×	×	×	Fmincon	OC
Standalone system [18]	✓	×	✓	×	×	✓	×	×	×	HOMER	COE, EE, CO ₂ emissions, DF, NPC and RF
Standalone system [19]	✓	×	✓	×	×	✓	×	×	×	HOMER	CO ₂ emission and NPC
Microgrid system [20]	✓	×	✓	✓	×	✓	×	×	×	MILP	OC
Standalone HMGS [21]	✓	×	✓	✓	×	✓	×	×	×	LFMF	COE, RFA and LPSP
Standalone HES [22]	✓	×	✓	✓	×	✓	×	×	×	MOSADE	COE, RFA and LPSP
Standalone HES [23]	×	×	✓	✓	×	✓	×	×	×	LTOT	COE, NPV and PB
HMGS [24]	✓	×	✓	✓	×	✓	×	×	×	PSO	COE, OEI and RI
Standalone HES [25]	×	✓	✓	✓	×	×	×	×	×	TS, SA and HS	TACS
HES [26]	×	×	✓	✓	×	×	✓	✓	×	MILP	OC, REU and RSs
Microgrid system [27]	×	×	✓	✓	×	×	✓	×	✓	HSMGWO	COE, DEP and LPSP

Grid-connected power system [28]	×	×	✓	×	×	×	✓	×	×	PLM and VPE	SPSO
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Many methods have been presented for the optimization of the grid-connected and island power systems. On the other hand, the effects of WTG, PV and ESS on the environmental, reliability voltage profile, power loss and economic performance of the distribution network have not been completely addressed. In line with the aforementioned research gaps, it is well established that the feasibility of RETs on the isolated power supply should be investigated. This provides affordable and uninterrupted power supply that will satisfy the load demands of rural communities without the needs for subsidies. The research work addresses the problem of power interruptions at the load centres with the utilization of RETs and their effects on the reliability performance of the network. This provides a global solution that is more realistic to increase the economic activities in rural communities that have not been connected to the utility grid owing to some technical and financial limitations. The proposed model will serve as a potential solution for improvement of the reliability of power system and other electrification projects in rural areas that fall within the same economic constraints. The methodology adopted in the study allows different configurations of RETs to be evaluated for economic viability of power generation. This paper is focused on uninterrupted electricity supply at the load centres with the application of renewable energy resources and the financial model that will make it to be economically feasible. The outcomes of the study can be used by the power system’ designers, planners and operators to determine the balance between economy and continuity of power supply.

This research work is designed to accomplish an overall improvement in the performance of the distribution network by using various combinations of RETs that can fulfill the power requirements of the proposed microgrid system. The proposed method is implemented in a RBTS bus 4 distribution networks to achieve the objectives of the study and to exploit the techno-economic benefits of RETs in the power systems. In this paper, the general overview of the RETs with their components and configurations is presented to increase the reliability and efficiency of a microgrid system with the utilization of the necessary data, models and some KPIs. The research work is also designed to improve the voltage profile and reduce power loss of the power system. The outcomes of this research work can be used by the utilities as benchmark to harness the benefits of local renewable energy sources to achieve sustainable energy development goal. The study also introduces a technique that can be utilized to measure the effects of the WTG, PV and ESS in a microgrid system. The research gaps obtained from the literature review show the need to develop a model to optimize the TAC, EIR, TOC, EIR, P_L and V_D simultaneously by using multiple power sources. The major contributions of this study include:

- i. Presentation of a model that can be utilized to assess the performance of the power system with the utilization of RETs based on the government policies and design specifications.

- ii. Development of a model that can be used to estimate the technical, economic and environmental impacts of RETs in the power system.
- iii. Presentation of an energy management framework that relies on the efficient use of renewable energy resources.
- iv. Presentation of economic analysis that can be used to determine the balance between economy and continuity of the power supply.
- v. Presentation of a concept to increase global access to electricity with the utilization of RETs.
- vi. Development of a model that will allow the stakeholders in the power sector to make a meaningful investment decision based on the numerous available energy resources.

The outcomes of the study will pave way for utilization of RETs to meet the global power demand and reduce over 849 million individuals that currently have no access to electricity in the world. The rest of part of the paper is arranged as follows: In Section 2, microgrid system and generation models for their various components are presented. Meanwhile, the problem formulation coupled with the power system constraints is presented in Section 3. The effects of RETs on the reliability of the power system are explained in Section 4. In Section 5, the technical specifications and cost parameters that are presented. The simulation results and discussions with a number of scenarios are presented in Section 6. Finally, conclusions are drawn in Section 7.

2. Microgrid system

A microgrid is a subsystem of a power system that includes DG, ESS, PV, WTG and load. The microgrid systems are localized power system that allows the utilization of RETs to satisfy load demand within the network [18]. The microgrid systems can be utilized by the MGOs to mitigate grid disturbance, reduce load shedding and meet critical loads. A microgrid system can be configured in either island mode or grid-connected system based on the distribution system fault conditions, the nature of the loads, flexibility of the network, etc. The microgrid systems should be able to restore the power supply within a short duration by using RETs at a low operating cost. The ability to operate in the standalone mode will considerably intensify the local reliability of the system. Owing to this, microgrid system is a prospective solution for the enhancement of the technical, economic and environmental performance of the power system [29], [30]. The capacity, location, operation and availability of RETs are the determinant factors that influence the technical, economic and environmental performance of the power system [31], [32]. The effects of the aforementioned factors are essential to be evaluated during the design and planning phases of the microgrid systems. The substantial impacts of RETs on the TAC, EIR, TOC, IR, P_L and V_D of a microgrid system can be computed by using the models proposed in the study.

2.1. Wind turbine generator model

The electrical power output of the WTG is a function of some significant factors such as selected sites, the power curve of the WTG selected for power generation, the wind speed, etc. The power generated by the WTG at a particular wind speed can be estimated by utilizing the power curve made available by the manufacturer of the turbines. The relationship between the speed of the site selects for the project and power output of the WTG can be expressed as:

$$P_{wtg}(v(t)) = \begin{cases} 0 & \text{for } 0 \leq v(t) \leq v_{cut-in} \\ a \times v^k + b \times P_r & \text{for } v_{cut-in} \leq v(t) \leq v_{rated} \\ P_r & \text{for } v_{rated} \leq v(t) \leq v_{cut-out} \\ 0 & \text{for } v(t) > v_{cut-out} \end{cases} \quad (1)$$

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

The mathematical model to estimate the power delivered by the WTG can be expressed in Eq. (2) as:

$$P_{wtg-out} = P_{wtg}(v(t)) \times A_{wtg} \times \eta_{wtg} \quad (2)$$

2.2. PV systems model

The output power of the PV system can be determined based on the size of the PV panel, ambient temperature, solar irradiation, efficiency of the PV panel and longitude and latitude of the site where the PV panel is installed. The power produced by the PV on the hourly basis is presented in Eq. (3) as [11]:

$$P_{pv}(t) = A_{pv} \times I_{pv}(t) \times \eta_{pv} \quad (3)$$

2.3. Energy storage system

The ESS is a device that consists of electrochemical cells and it can be used by the MGOs to convert the stored chemical energy to electrical energy. The ESS can be utilized to support the operations of the RETs in the distribution network owing to fluctuations of solar and wind resources. The ESS is utilized by the MGOs based on its capability to reduce the effects of the peak loads on the optimal operation of a microgrid system and smooth out the influences of wind and solar resources on the power system [33]. The application of the ESS can provide a potential solution to upgrade the aging traditional power network and bridges the gap between the customer's load demand and utilities [34]. It has become a crucial device to provide emergency and standby supports for the utilities, reduce electricity bills and increase revenue. The ESS is used in the microgrid systems to maintain the power balance between the power produced by RETs and the load demand. The state of charge (SOC) of the ESS at the time t is presented in the following expression [35].

$$SOC(t) = SOC(0) + \eta_c \sum_{t=1}^k P_{ess}^{ch}(t) - \eta_d \sum_{t=1}^k P_{ess}^{dis}(t) \quad (4)$$

The ESS is designed by the MGOs to operate within the minimum and maximum allowable capacities specified by the manufacturers.

$$SOC^{\min} \leq SOC(0) + \eta_c \sum_{t=1}^k P_{ess}^{ch}(t) - \eta_d \sum_{t=1}^k P_{ess}^{dis}(t) \leq SOC^{\max}, \text{ for } 1 \leq t \leq k \quad (5)$$

The operation of the ESS is a function of the depth of discharge (DOD) as expressed in Eq. (6) as:

$$SOC^{\min} = (1 - DOD) SOC^{\max} \quad (6)$$

The battery depth of discharge is always between 30-50% based on the specifications of the original equipment manufacturers. This will increase the performance and prolong the life span of the battery.

2.4. Diesel generator

The DG is very expensive to run due to high maintenance cost and fuel cost, it is not environmentally friendly owing to high greenhouse gas (GHG) emission that is associated with its operation. The DG can be combined with other RETs as a measure to increase the reliability and simultaneously minimize the FC, MC and EC of the power system [36]. The FC of the DG diesel can be presented in Eq. (7) as [32]:

$$FC_i = a_i P_{gen}^2(i,t) + b_i P_{gen}(i,t) + c_i \quad (7)$$

3. Objective function

The research work is structured to assess the impacts of RETs on the technical, economic and environmental performance of the proposed power system under certain constraints. This will reduce the power outage experienced at the load centres and the operating cost of a microgrid system as presented in Fig. 1. The objective of the study is to increase the performance of a power system by minimizing the TOC, RI, TAC, EIR of pollutant ith , P_L and V_D . The performance of the proposed microgrid system can be estimated by utilizing the aforementioned operating parameters. This can be accomplished with the utilization of RETs in the power system so that the load demand is shared among the DG, ESS, WTG and PV units. The fmincon optimizer is utilized in the study due to the following advantages: the best possible solution can be obtained with the solver, it is efficient to produce an optimal result, it has the high proficiency to solve multi-objectives problems that have numerous constraints as quickly as possible, it is highly flexible and efficient to resolve multi-objective problems and it is a state of the art of the optimisation method that operates with a low computational time. The objective function of the study is focused on the technical, economic and environmental analysis of the distribution

network by utilizing an intelligent optimal control method based on the MATLAB fmincon solver as presented in Eq. (8).

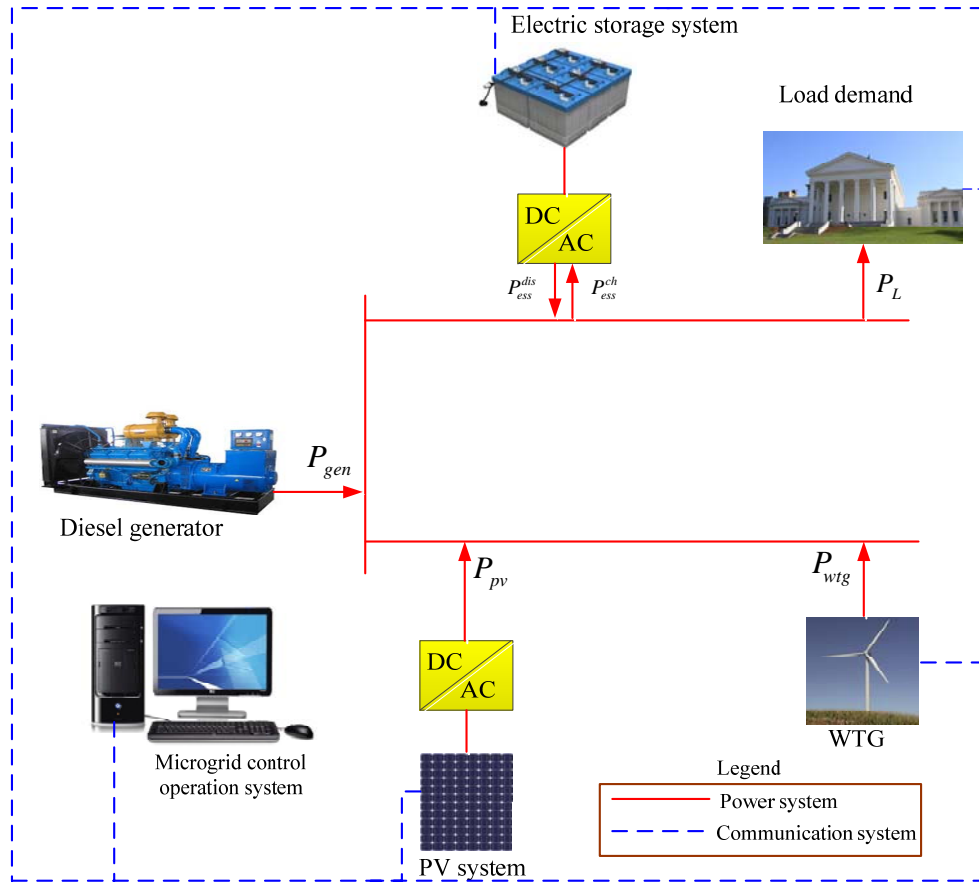


Fig. 1 Configuration of the PV/wind/battery/diesel microgrid power system

$$f = \min \sum_{i=1}^n (TOC_i + RI_i + TAC_i + EIR_i + P_{L,i} + V_{D,i}) \quad (8)$$

The first element of the objective function is the total outage cost that is estimated by considering the cost of consumer' dissatisfaction, expected interruption cost (ECOST) and expected energy not supplied index (EENS) of the system at the load centres. The TOC is applied in the study to evaluate the impact of power outages with the application of RETs based on the cost of customer' dissatisfaction due to power interruption that is measured in $\$/kWh$ [37], [38]. The TOC of the proposed power system is presented in Eq. (9) as:

$$TOC_i = \sum_{i=1}^n (k_{cc} \times EENS_i + ECOST_i) \quad (9)$$

The cost of customer' dissatisfaction due to power interruption can be estimated as presented in Eq. (10) [39]:

$$k_{cc} = \left\{ \frac{\sum_{i=0}^n (VF_i \times EDC_i) + \sum_{j=0}^n ISC_j}{\sum_{i=0}^n EENS_i} \right\} (\$/kWh) \quad (10)$$

$$= \left\{ \frac{\sum_{i=0}^n (VF_{com,i} \times EDC_{com,i} + VF_{ind,i} \times EDC_{ind,i} + VF_{r,i} \times EDC_{r,i} + VF_{g\&i,i} \times EDC_{g\&i,i} + VF_{o,i} \times EDC_{o,i}) + \sum_{j=0}^n (TIC_{jx} - IC_{jy})}{\sum_{i=0}^n EENS_i} \right\}$$

The second element of the objective function is the reliability index that is introduced to estimate the overall reliability performance of a microgrid system with the integration of RETs.

$$RI = w_1 \frac{SAIFI}{SAIFI_T} + w_2 \frac{SAIDI}{SAIDI_T} + w_3 \frac{EENS}{EENS_T} + w_4 \frac{ECOST}{ECOST_T} \quad (11)$$

$$\sum_{i=1}^n w_i = 1 \quad (12)$$

where w_i is the weighted factor of i index and n is the number of indices. The values of the weighted factors depend on the importance of the reliability index to be considered.

The third element of the objective function is the total annual cost that consists of CC, FC, MC and EC of the generating unit i . The MC, FC and EC, CC, TAC of the power system can be estimated by utilizing equations (13) - (21).

$$MC = \sum_{i=1}^n \left\{ C_{amain_{gen,i}} + C_{amain_{pv,i}} + C_{amain_{wtg,i}} + C_{amain_{ess,i}} + C_{amain_{inv,i}} \right\} \quad (13)$$

The annualized maintenance cost (C_{amain}) for the components of a microgrid system can be estimated by utilizing Eq. (14) as:

$$C_{amain, i} = MC_{i,j} \times \eta_{cr,i} (1 + f)^{P_{proj,i}} \quad (14)$$

$$FC = \sum_{i=1}^n \left\{ a + bP_{gen} + cP_{gen}^2 \right\} \$/yr \quad (15)$$

The annualized emission cost of the power system can be assessed as presented in Eq. (16) [33]:

$$EC = (\alpha_i EF_{NO_{x,i}} P_{gen} + \alpha_j EF_{SO_{2,i}} P_{gen} + \alpha_k EF_{CO_{2,i}} P_{gen}) \$/yr \quad (16)$$

The GHG emissions produced by the DG such as CO₂, SO₂ and NO_x can be assessed by using Eq. (17).

$$\left\{ \begin{array}{l} GHG_{CO_2} = EF_{CO_2,i} P_{gen} \\ GHG_{SO_2} = EF_{SO_2,i} P_{gen} \\ GHG_{NO_x} = EF_{NO_x,i} P_{gen} \end{array} \right\} \text{ (kg/yr)} \quad (17)$$

The capital cost of the power system can be expressed as:

$$CC = \left\{ \begin{array}{l} \sum_{i=1}^n (CRF_{gen,i} \eta_{gen,i} C_{gen,i}) + \sum_{i=1}^n (CRF_{pv,i} \eta_{pv,i} C_{pv,i}) \\ + \sum_{i=1}^n (CRF_{wtg,i} \eta_{wtg,i} C_{wtg,i}) + \sum_{i=1}^n (CRF_{ess,i} \eta_{ess,i} C_{ess,i}) \\ + \sum_{i=1}^n (CRF_{invt,i} \eta_{invt,i} C_{invt,i}) \end{array} \right\} \quad (18)$$

The capital cost ($C_{x,i}$) of each component can be estimated by using the equation presented as follows: consists of the initial unit cost of the components and installation cost.

$$C_{x,i} = (x\% + 1) \times C_{cap,x,i} \quad (19)$$

The CRF for the proposed power system can be estimated as:

$$CRF = \frac{i(i+1)^{proj}}{(1+i)^{proj} - 1} \quad (20)$$

The total annual cost of a microgrid system is expressed in Eq. (21) as:

$$TAC = \left\{ \sum_{i=1}^n CC_i(t) + \sum_{i=1}^n FC_i(t) + \sum_{i=1}^n MC_i(t) + \sum_{i=1}^n EC_i(t) \right\} \quad (21)$$

The fourth element of the objective function is the EIR that can be utilized for the reduction of pollutant ith. It can also be used to estimate the benefits of emissions reduction with the application RETs in a microgrid system. The environmental advantages of RETs in a microgrid system can be estimated as follows:

$$EIR_i = \frac{PE_{i/wRETs}}{PE_{i/woRETs}}, \text{ for pollutant ith such as NO}_x, \text{ SO}_2 \text{ and CO}_2 \quad (22)$$

$$PE_{i/wRETS} = \sum_{i=1}^n P_{gen,i}^w(t) y_{ik}(t) \quad (23)$$

$PE_{i/woRETS}$ depicts the quantity of GHG emissions from the DG without utilizing RETs.

$$PE_{i/woRETS} = \sum_{i=1}^n P_{gen,i}^{wo}(t) y_{ij} \quad (24)$$

The fifth element of the objective function is the P_L that can be reduced with the application of RETs subject to the constraints of the distribution system. The P_L can be classified into real power loss and reactive power loss that are briefly presented as follows:

The active power loss of the system is presented as follows:

$$P_{loss,a} = \sum_{i=1}^{nbr} R_i \times \frac{P_i^2 + Q_i^2}{V_i^2} \quad (25)$$

The reactive power loss ($P_{loss,re}$) of the system is presented as follows:

$$P_{Loss,re} = \sum_{i=1}^{nbr} X_i \times \frac{P_i^2 + Q_i^2}{V_i^2} \quad (26)$$

The last element of the objective function is the V_D that is one of the most significant power-quality and security index that must be improved subject to the system constraints. It can be expressed as follows:

$$V_D = \sum_{j=1}^{nbr} |V_i - V_j|, k = 1, 2, \dots, n \quad (27)$$

V_i is the nominal voltage and V_k is the real voltage up to the j^{th} bus.

3.1. Constraints of the power system

The objective function presented in the study is designed with a number of the generating units that operate within their specific minimum and maximum constraints as presented as follows:

3.1.1. Power balance limits

The power demand is satisfied by the power generated by the DG, WTG, PV and ESS as presented in Eq. (28) as:

$$\sum_{i=1}^n P_{gen}(t) + \sum_{i=1}^n P_{pv}(t) + \sum_{i=1}^n P_{wtg}(t) + \sum_{i=1}^n P_{ess}^{dis}(t) - \sum_{i=1}^n P_{ess}^{ch}(t) - \sum_{i=1}^n P_{loss,a}(t) = \sum_{i=1}^{LP^{load}} P_{Di}, \quad \left\{ \begin{array}{l} 1 \leq t \leq n \\ 1 \leq t \leq LP^{load} \end{array} \right\} \quad (28)$$

where P_{gen} , P_{pv} and P_{wtg} denote power produced by the DG, PV and WTG. While P_{ess} depicts the output power from the ESS and P_D is the load demand.

3.1.2. Power generating output constraints of DG, PV, WTG and ESS

The control variable limits are the power produced by the WTG, PV, ESS and DG based on the technical specifications. The control variable limits of the microgrid system are expressed as follows:

$$\begin{cases} P_{gen,i}^{\min}(i,t) \leq P_{gen,i}(i,t) \leq P_{gen,i}^{\max}(i,t) \\ P_{pv,i}^{\min}(i,t) \leq P_{pv,i}(i,t) \leq P_{pv,i}^{\max}(i,t) \\ P_{wtg,i}^{\min}(i,t) \leq P_{wtg,i}(i,t) \leq P_{wtg,i}^{\max}(i,t) \\ P_{ess,i}^{ch,\min}(i,t) \leq P_{ess,i}(i,t) \leq P_{ess,i}^{ch,\max}(i,t) \\ P_{ess,i}^{dis,\min}(i,t) \leq P_{ess,i}(i,t) \leq P_{ess,i}^{dis,\max}(i,t) \end{cases} \quad (29)$$

3.1.3. Voltage constraints

The stable operation of the distribution power system can be maintained by restricting the load bus voltages to the lower and upper limits as follows [40]:

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad (30)$$

3.1.4. Current constraints

The line currents of the proposed distribution power system are bound by their minimum and maximum limits as expressed in Eq. (31) [41]:

$$0 \leq I_i \leq I_i^{\max} \quad (31)$$

3.1.5. Constraints of electric storage system

The capability of the ESS to work effectively in a microgrid system is based on its ability to operate within the allowable SOC limits as presented in Eq. (32) [11] as:

$$SOC^{\min} \leq SOC(t) \leq SOC^{\max} \quad (32)$$

4. Effects of renewable energy technologies on the reliability of the distribution network

The reliability of the distribution network is associated with a continuous power supply from the generating stations to the load centres since the availability of electricity is one of the significant factors for any modern economy [42]. The availability of an uninterrupted power supply is

significant to the rapid economic development of any nation. For this reason, the power systems should be structured in such a way to satisfy the power demand at a reasonable level of reliability [43]. The power utilities and the regulatory bodies analyse the performance of the distribution network by using the reliability indices. The reliability assessment can also help the MGOs and regulatory bodies to determine the best expansion strategies to provide reliable electricity to the customers. The reliability index can be used to estimate the number of customers affected by power interruption, the average length of power interruption and the number of power interruption [44]. The impacts of power outage mitigation techniques to increase the reliability of the distribution network can be quantified with the application of SAIFI, SAIDI, EENS and ECOST that have been extensively explained in [45]. The degree of service continuity from the supply points is measured with the utilization of the aforementioned reliability indices.

5. Operating parameters of the proposed microgrid system

The cost and technical specifications of the proposed microgrid system as presented in Table 2 are used in this research work. The optimal operation of the DG, WTG, PV and ESS can be assessed by considering the reliability performance and financial feasibility of the power system. The cost model that is applied in the research work is based on the technical parameters and costs of the components that are used to estimate the TAC, TOC, RI and EIR of the power system.

Table 2 Technical specifications of the proposed power system [46]-[49]

Description	Initial cost	Maintenance cost	Lifetime	Other operating parameters
DG	\$2700/kW	0.01258 \$/kWh	25000 hr	Capacity: 1280 kW, cost coefficients of the DG a: 2.4438, b: 208.21 and c: 5.968, Diesel fuel price: \$0.94/litre and Efficiency: 80%
WTG	\$3500/kW	20 \$/kW/year	25 yr	Capacity:1 MW, Model number: GEV HP 1000/62, V_{ci} :3 m/s, v_r :15 m/s, V_{co} : 25 m/s and swept area: 3019 m^2 .
PV	\$4000/kW	10 \$/kW/year	25 yr	Capacity: 300W, weight: 23.20kg, max power point voltage = 37.23 V, max power point current: 8.06A, current temperature coefficient: -0.05%/°C, voltage temperature coefficient: -0.34%/°C, Temperature Coefficient of Pmax: -0.45%/°C, operating temperature: -40°C to 85°C, open circuit voltage: 44.7 V, short circuit current: 8.95A, module efficiency: 15.46 %, cell efficiency: 17.46%, and dimensions of the PV panel: 1956mm×992mm×50mm.
ESS	\$1500/battery	10 \$/battery/year	5 yr	ESS: 200Ah, ESS max SOC: 90%, ESS min SOC: 40%, ESS discharging efficiency: 100% and ESS charge efficiency: 85%
Inverter	\$2500/kW	3 \$/kW	15 yr	Capacity: 1 kW and 30 kW

6. Results and discussions

The techno-economic effects of RETs in a microgrid system are assessed in this research work having utilized the following parameters: TOC, IR, TAC, EC, MC, FC, EIR, P_L and V_D . The aforementioned KPIs are used to carry out techno-economic analysis of the power system. The RBTS bus 4-distribution system is used in the study to examine the cost effectiveness of the model in the proposed microgrid system and the sequential hourly power demand shape of the IEEE-RTS is utilized in the research work with the peak load of 40 MW. The system comprises of 38 load points, 7 feeders, 26 switches and 31 transformers. The line data, repair time, failure rate, customer and load point parameters, bus data, transformer data, feeder data and other operating parameters used in the study are available in [42], [50]-[52]. The RBTS bus 4-distribution system is a well-known test system that has been frequently used in many research works to carry out the reliability studies of the distribution networks. The respective power loss reduction and voltage profiles in each scenario are compared to estimate the impacts of RETs. This shows that the comparison of percentage bus voltage improvement can be made before and after integration of RETs into the distribution system. The schematic diagram of the proposed power system is presented in Fig. 2 with some modifications. The proposed microgrid system is categorized based on the configurations of the scenarios as presented in Table 3. To understand the concept of RETs and their effects on the performance of a microgrid system, the following scenarios are considered in the study:

- ❖ Scenario 1: Diesel generator only
- ❖ Scenario 2: Diesel generator and PV system
- ❖ Scenario 3: Diesel generator and WTG system
- ❖ Scenario 4: Diesel generator, PV system and WTG system
- ❖ Scenario 5: Diesel generator, PV system, WTG system and ESS

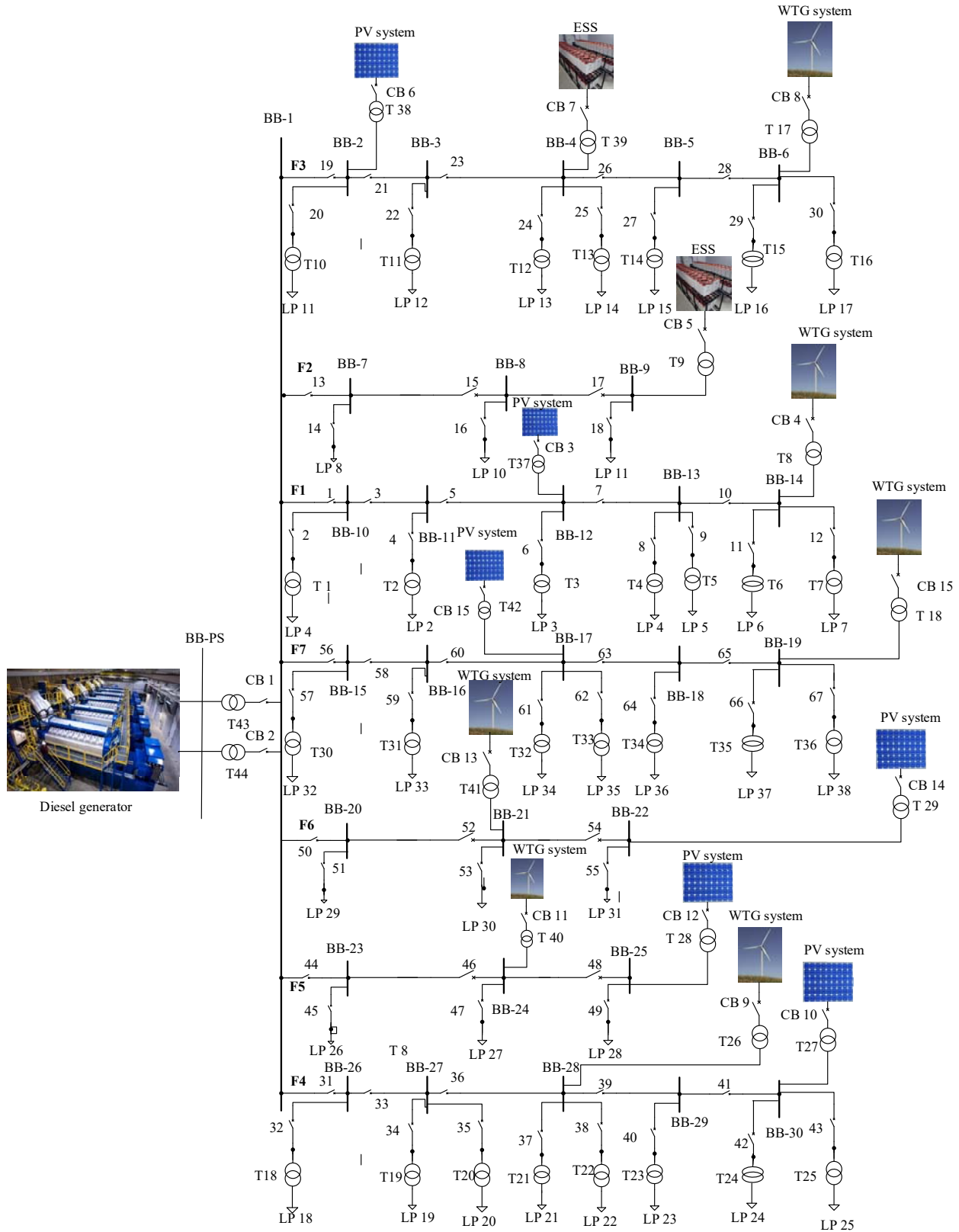


Fig. 2 Modified RBTS distribution system [50], [51]

Table 3 Configuration of the scenarios

Scenarios	Diesel (MW)	Generator	PV (MW)	WTG (MW)	ESS (MW)
1	48.64		0	0	0
2	48.64		24	0	0
3	48.64		0	24	0
4	48.64		24	24	0
5	48.64		24	24	4

6.1. Performance of the proposed microgrid system

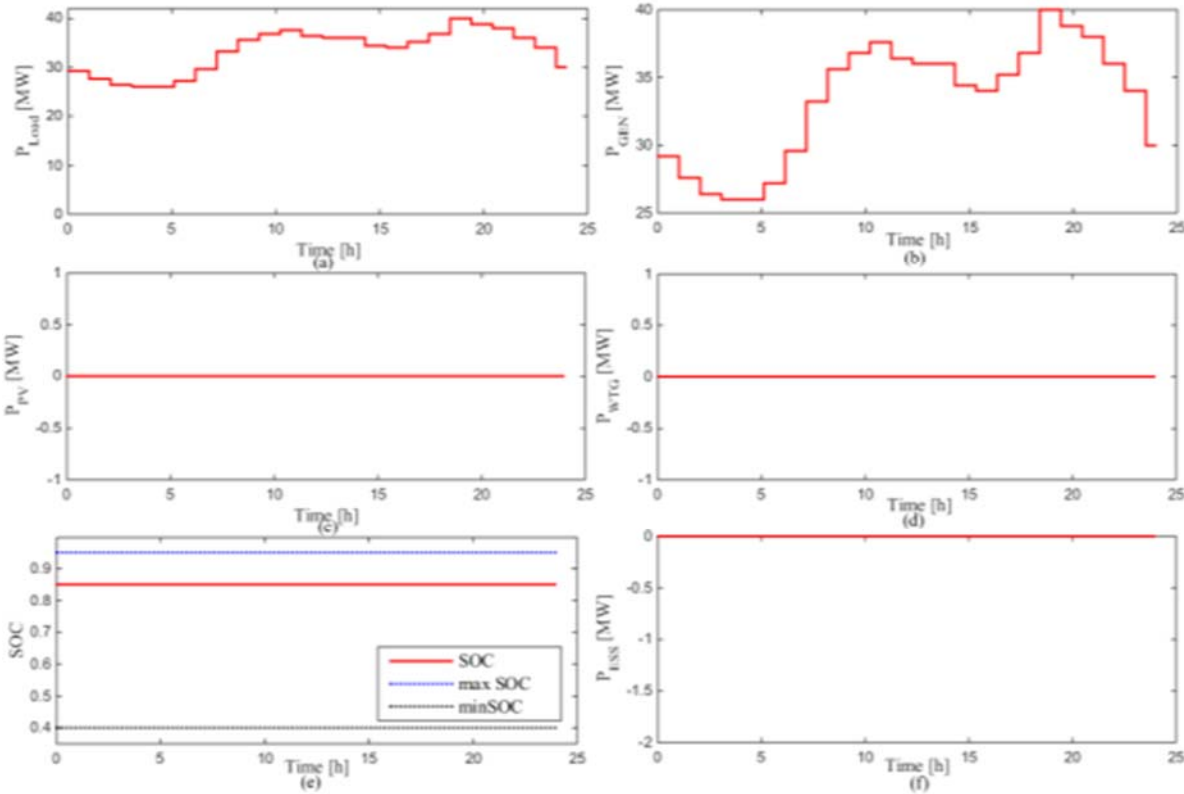
The performance of a microgrid system is investigated in this section by using five scenarios with the utilization of the WTG, PV and ESS in the distribution system. The results obtained from the scenarios are presented as follows:

Scenario 1: DG only

In this scenario, the system consists of only the DG with the installed capacity of 48.64 MW power to fulfill the demand at the load centres. The results of variation of the system load and power output of each unit are shown in Fig. 3 (a-f). It can be observed that the DG is producing 100% of the entire power requirements. The breakdown of the TAC for this scenario is presented in Fig. 4, where FC has the largest share of the TAC with 50.42%, follows by CC with 36.27% . Meanwhile, the TAC, CC, FC, MC and EC of the system are \$169379658/yr, \$61442322/yr, \$85407000/yr, \$16952936/yr and \$5577400/yr as shown in Fig. 5 and Table 4. Similarly, it can be seen from Table 5 and Fig. 6 (a-c) that the values of CO₂, SO₂ and NO_x are 192020000 kg/yr, 105080 kg/yr and 1955700 kg/yr. The values of GHG emissions are very high in this scenario because the level of RETs penetration is zero and the value of EIR is high as presented in Fig. 7. This scenario has the highest value of EIR (100%) because it does not operate with the integration of RETs. The amount of fuel consumption by the DG is 93854000 L/y as presented in Table 6. The fuel consumption of the DG can further be reduced with the incorporation of RETs. It is well established that the operation of the proposed microgrid system becomes worse when it is entirely based on the DG alone. The results show that the system relies only on the DG that is not economically and environmentally viable based on the high fuel and emission costs.

The RI of the system is 1 as shown in Fig. 8 and this indicates the values of SAIDI, SAIFI and AENS are very high while the value of CAIDI is low owing to the failure rates of the power system as presented in Table 7. Furthermore, it can be observed from Table 7 that the value ECOST is \$715972.1 /yr, EENS is 137.027 MWh/yr and TOC is \$1469620.6/yr. The values of ECOST, TOC and EENS recorded in this scenario are very high owing to the fact that the DG is used alone to satisfy the power requirements and because of the faulty components in the distribution system. This indicates that generation entirely on a single power source cannot guarantee the best reliable power supply. The active and reactive power losses recorded in this scenario are 437.2 kW and 439.3 kVAr as shown in Fig. 9. Similarly, the voltage deviation obtained in this scenario 1 is 2.27084 V as presented in Fig. 10 and it can be minimized with the

application of RETs based on the voltage variation at each bus bar presented in Fig. 11. The results obtained from scenario 1 such as power losses and voltage deviations are compared with other scenarios to justify the influences of RETs in the power system.



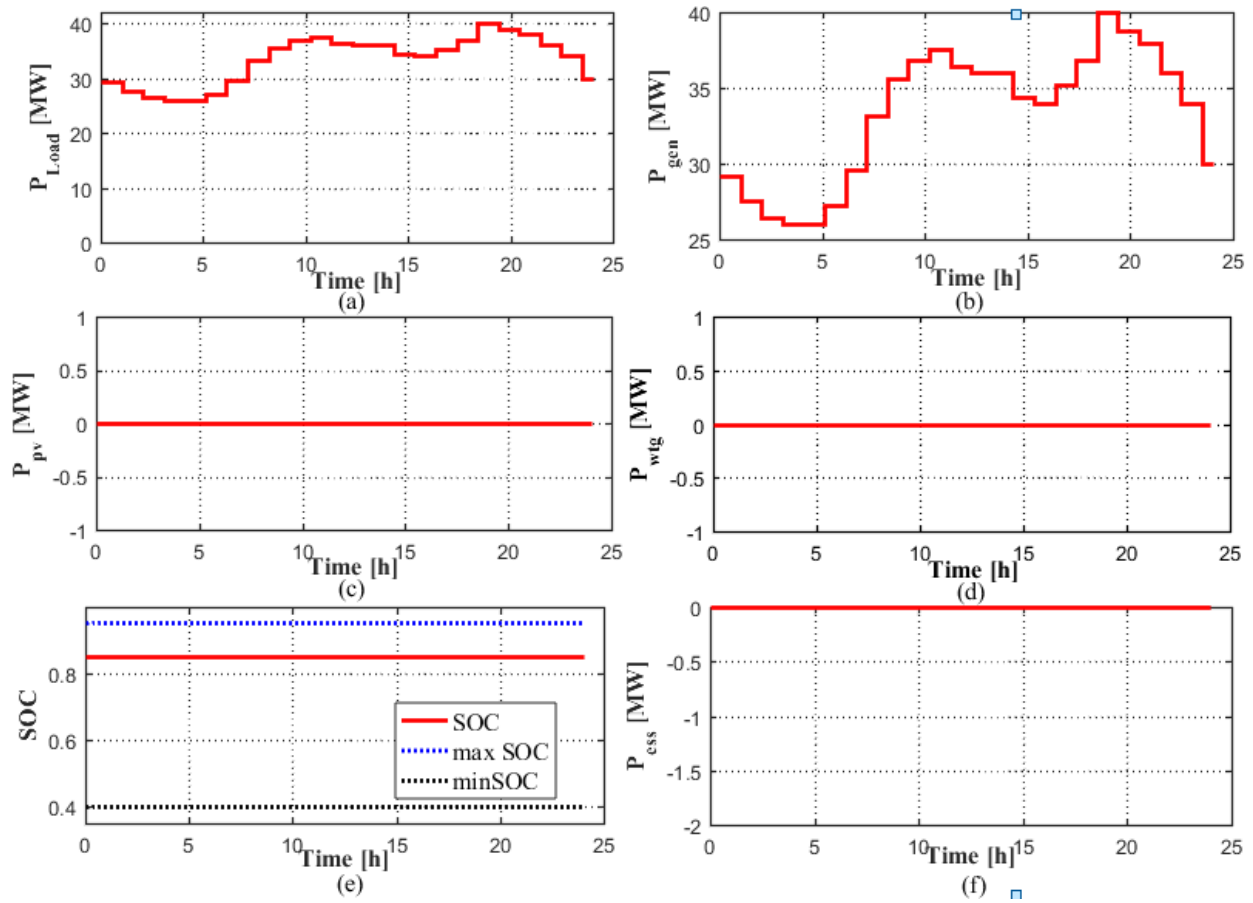


Fig. 3 Scenario 1: variation of (a) load demand, (b) power from the DG, (c) power from the PV system, (d) power from the WTG system, (e) SOC and (f) power from the ESS.

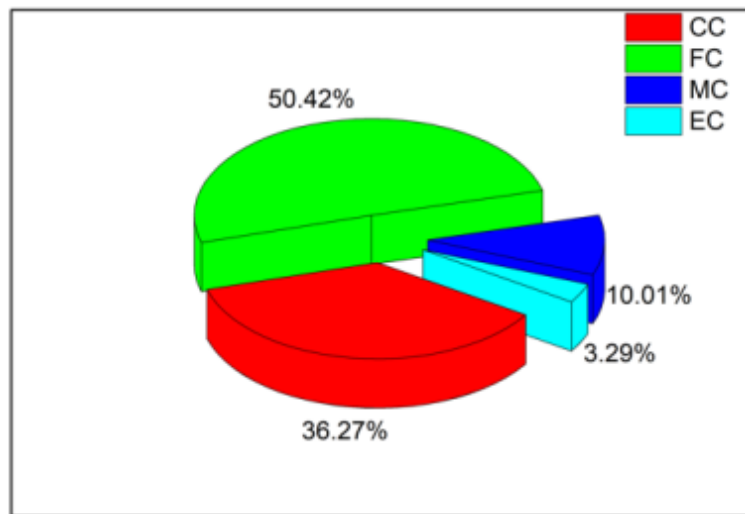


Fig. 4 Breakdown of the total annual cost for scenario 1

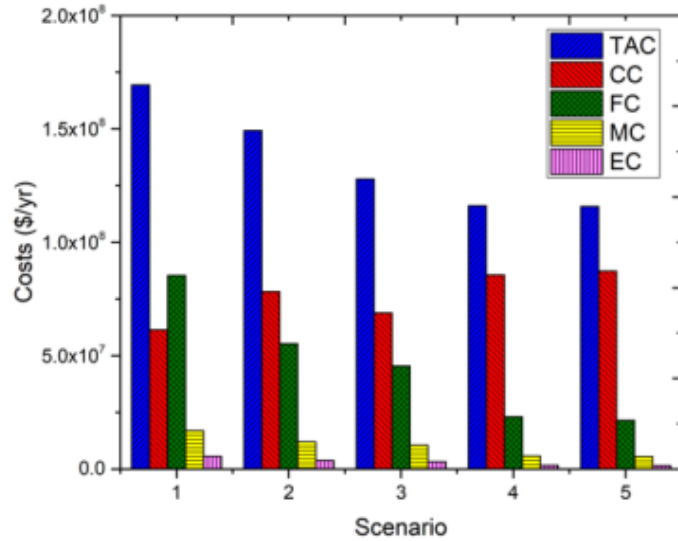


Fig. 5 Total annual cost of the system

Table 4 Economic effects of the ESS, PV and WTG in the power system

Description	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
CC (\$/yr)	61442322	78219697.74	68830235	85607611	87268721
FC (\$/yr)	85407000	55298000	45394000	23040000	21513000
MC (\$/yr)	16952936	11941000	10460000	5780300	5514500
EC (\$/yr)	5577400	3849700	3283400	1664800	1564200
TAC (\$/yr)	169379658	149308397.7	127967635	116092711	115860421
TAC savings (\$/yr)		20071259.79	41412023	53286947	53519236
TAC savings (%)		11.84986443	24.449231	31.460063	31.597204
Improved cost saving of MC (\$/yr)		5011936	6492936	11172636	11438436
Improved cost saving of FC (\$/yr)		30109000	40013000	62367000	63894000
Improved cost saving of EC (\$/yr)		1727700	2294000	3912600	4013200
Improved cost saving of MC (%)		29.56382	38.29977	65.90384	67.47171
Improved cost saving of FC (%)		35.25355	46.84979	73.02329	74.8112
Improved cost saving of EC (%)		30.9768	41.13028	70.15097	71.95467

Table 5 Effects of using ESS, PV and WTG on emission

Scenarios	CO ₂ emission (kg/yr)	SO ₂ emission (kg/yr)	NO _x emission (kg/yr)
1	192020000	105080	1955700
2	132540000	72570	1349900
3	113040000	61859	1151300
4	57315000	31364	583770
5	53852000	29469	548500

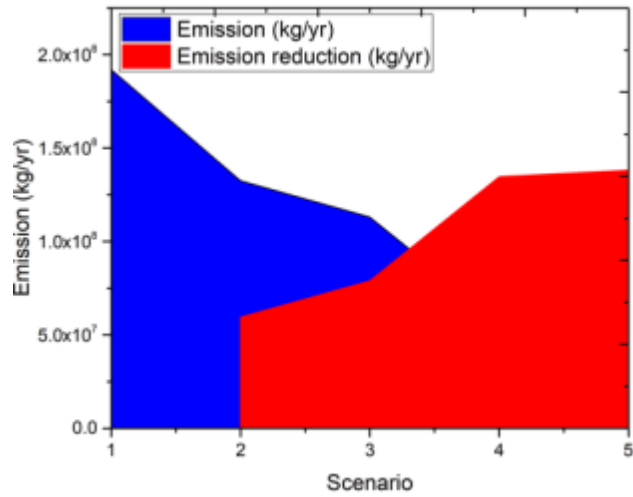


Fig.6a Quantity of CO₂ emission and its value with ESS, PV and WTG

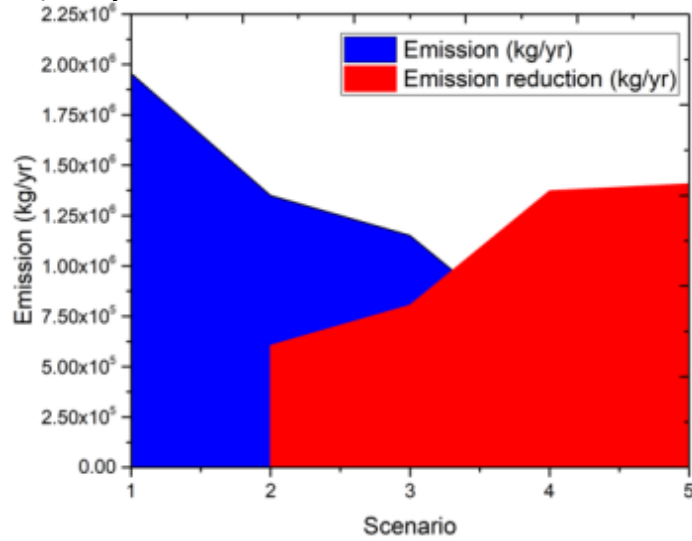


Fig.6b Quantity of NO_x emission and its value with ESS, PV and WTG

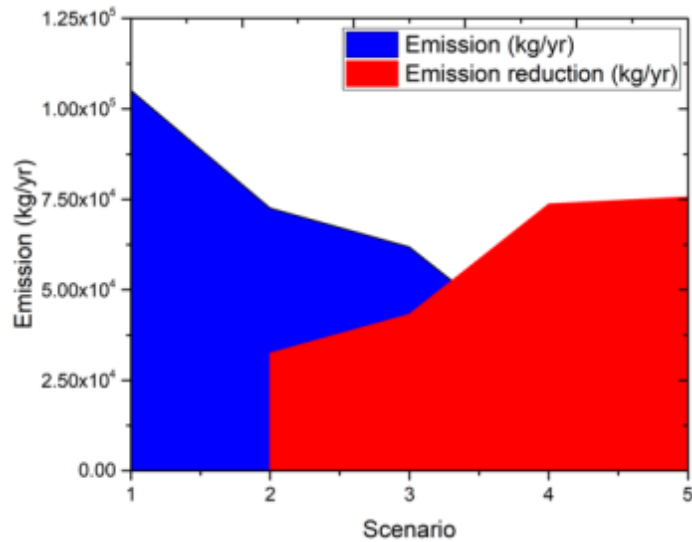


Fig.6c Quantity of SO₂ emission and its value with ESS, PV and WTG

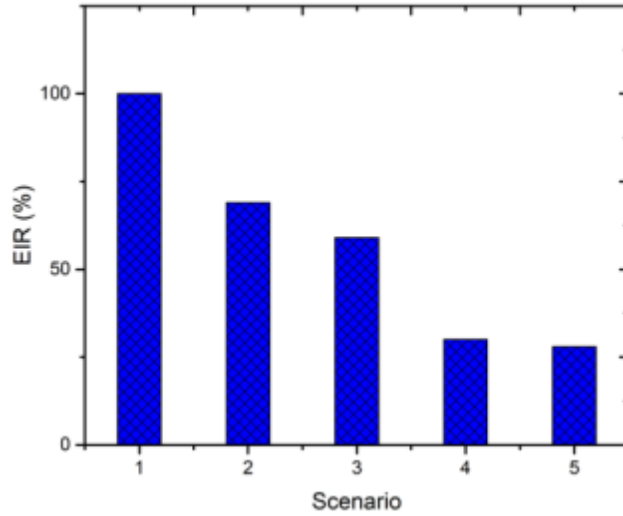


Fig.7 Impacts of ESS, PV and WTG on the emission reduction

Table 6 Effects of incorporating numbers of ESS, PV and WTG on fuel consumption

Scenarios	Fuel (L/yr)	Fuel saving (L/yr)	Fuel saving (%)
1	93854000		
2	60767000	33087000	35.2536919
3	49884000	43970000	46.84936177
4	25319000	68535000	73.02299316
5	23641000	70213000	74.81087647

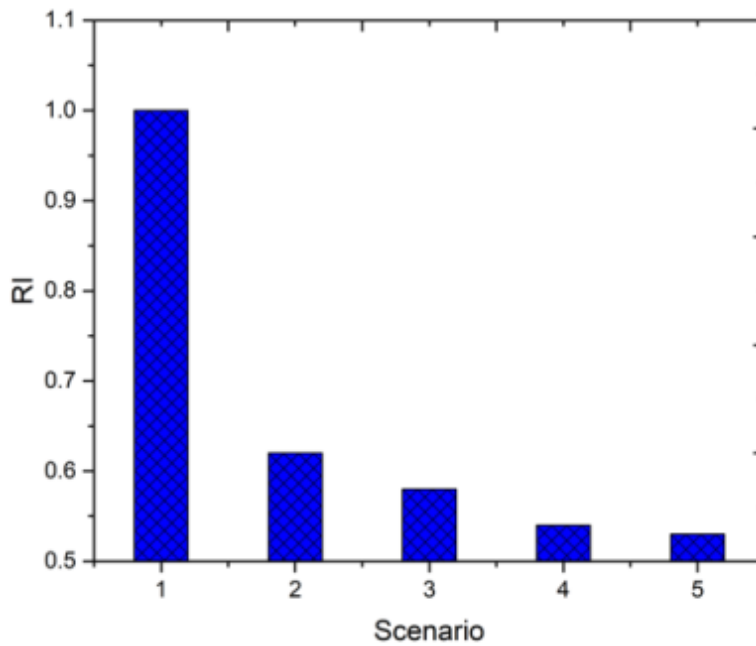


Fig.8 Reliability index for the whole system scenario

Table 7 Reliability performance of the distribution system with ESS, PV and WTG

Description	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
SAIFI (f/customer.yr)	0.9241	0.2415	0.1703	0.1308	0.1307
SAIDI (hr/customer.yr)	5.5199	4.0557	3.7331	3.5549	3.5546
CAIDI (hr/customer interruption)	5.973	16.792	21.917	27.180	27.192
AENS (Mhr/customer year)	0.0287	0.0207	0.0203	0.0189	0.0186
IEAR (\$/kWhr)	5.225	5.490	5.632	5.666	5.652
EENS (MWh/yr)	137.027	99.081	96.851	90.511	88.855
ECOST (\$/yr)	715972.1	543954.5	545510.1	512842	502213.9
Kcc*EENS (\$/yr)	753648.5	544945.5	532680.5	497810.5	488702.5
TOC (\$/yr)	1469620.6	1088900	1078190.6	1010652.5	990916.4
Improved cost savings of EENS (\$/yr)		208703	220968	255838	264946
Improved cost savings of EENS (%)		27.692	29.320	33.947	35.155
Improved cost savings of ECOST (\$/yr)		172017.6	170462	203130.1	213758.2
Improved cost savings of ECOST (%)		24.026	23.808	28.371	29.856
Improved TOC savings (\$/yr)		380720.6	391430	458968.1	478704.2
Improved TOC savings (%)		25.906	26.635	31.230	32.573

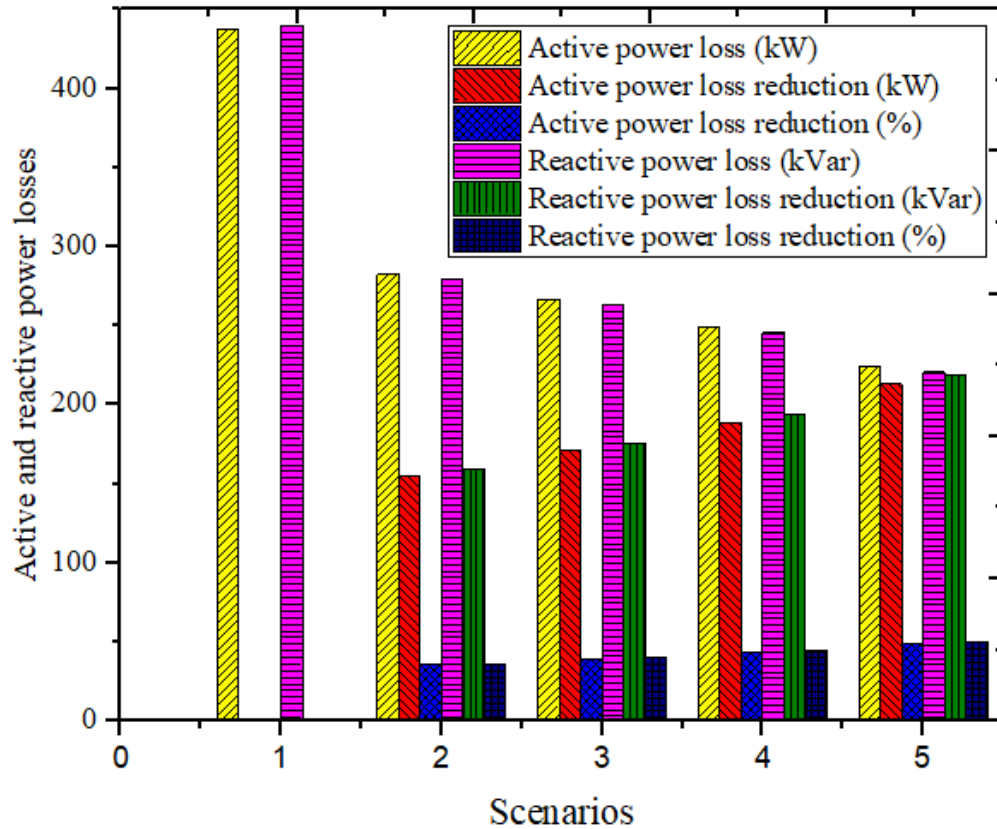


Fig. 9 Active and reactive power losses of the proposed power system with different scenarios

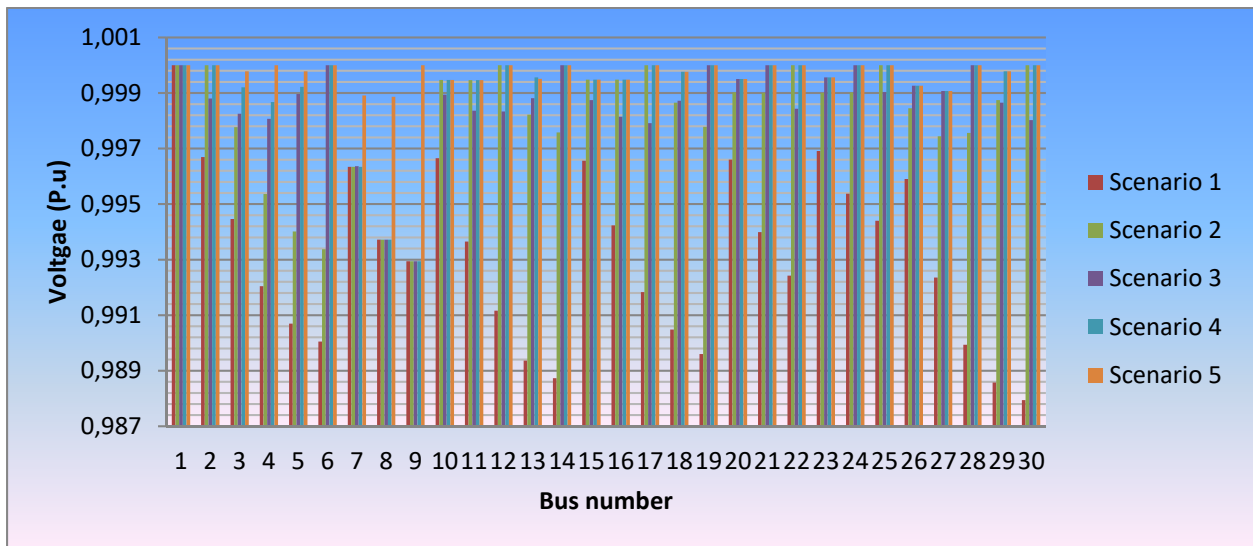


Fig. 10 Voltage profile of the proposed distribution power system based on each scenario.

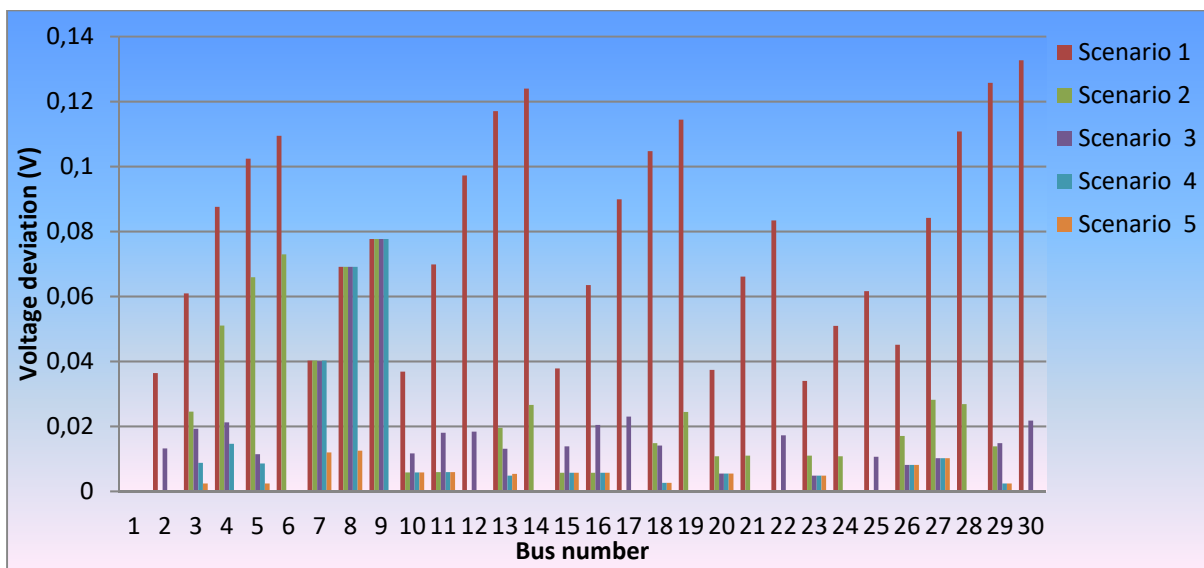


Fig. 11 Voltage deviation at each bus bar

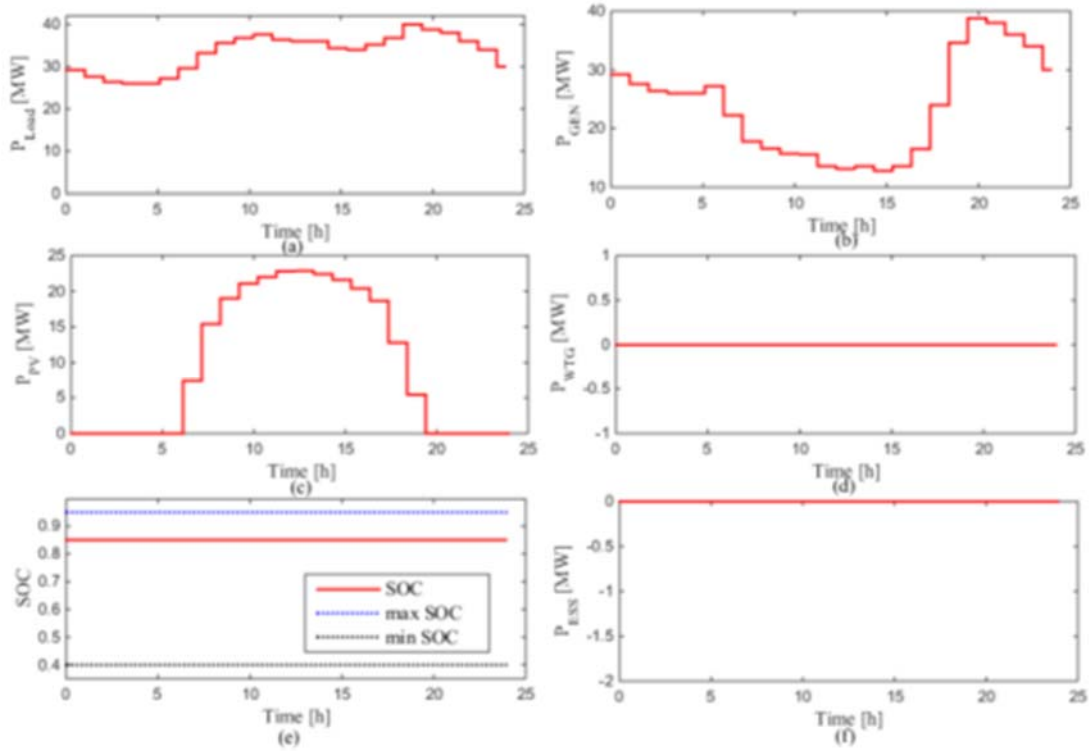
Scenario 2: DG and PV system

The economic, reliability and environmental impacts of the PV system on the existing power system is evaluated by using scenario 2. The application of the PV system reduces the stress on the DG and improves the efficiency and reserve merging of the system. The contributions of all the components of the power system are shown in Fig. 12 (a-f). With the application of the PV system in the existing power system, the DG is operating at less than half of the installed capacity as presented in Fig. 12 (b-c). The breakdown of the TAC for this scenario is presented in Fig. 13 where CC has the largest share of 52.39%. Moreover, the TAC, CC, FC, MC and EC of the power system are \$149308397.7/yr, \$78219697.74/yr, \$55298000/yr, \$11941000/yr and

\$3849700/yr as shown in Fig 5 and Table 4. The abovementioned values are lower than the first scenario owing to the high degree of the PV system penetration into the existing power system. The incorporation of the PV system into the base power system has contributed a major impact to the minimization of operating costs in terms of TAC, FC, MC and EC of the system as presented in Table 4 and Fig. 14. Hence, the cost savings of TAC, FC, MC and EC of the system have improved by 11.85%, 35.25%, 29.56% and 30.98% respectively as presented in Table 4 and Fig.15.

The quantity emission of CO₂ is 132540000 kg/yr, SO₂ is 72570 kg/yr and NO_x is 134990 kg/yr as presented in Table 4 and Fig. 6a-c. The values of GHG emissions are lower than scenario 1 because the level of incorporating the PV system into the base power system. The emission performance of a microgrid system with the utilization of the PV system is compared to a base system that operates only with the DG by using the EIR. The EIR is used as the KPI to estimate the impact of the PV system on emission reduction. The value of EIR obtained in this scenario is 69% as presented in Fig. 7. The fuel consumption in this scenario is 60767000 L/yr as shown in Table 6 and Fig. 16, this indicates that the deployment of the PV system in the proposed microgrid system has improved the fuel consumption saving of the DG by 35.25% as shown in Table 6 and Fig. 17. In this scenario, the reliability indices are evaluated to study the effects of installing the PV system on the entire distribution network. The results presented in Table 7 have established that the PV system has a considerable effect on the availability of power supply at the load centres. The reliability indices for instance SAIFI, SAIDI, CAIDI and AENS have improved substantially by 73.87%, 26.53%, 64.43% and 27.87% respectively. This is attributed to the drastic reduction in the duration and frequency of power interruption experienced by consumers at the respective load points. The RI of the system is 0.62 as shown in Fig. 8, this demonstrates that the reliability of the system is better than the first scenario. Moreover, it can be established from Table 7 that the value of ECOST is \$543954.5/yr, EENS is 99.081 MWh/yr and TOC is \$1088900/yr for this scenario. The cost savings of ECOST, EENS and TOC have increased by 24.026%, 27.092% and 25.906% respectively as shown in Table 7 and Fig. 18. The system reliability is found to have increased considerably with the penetration of PV system. Hence, the combination of the DG and PV system offers a better reliability when compared with the first scenario.

The integration of PV into the existing power system plays a prominent role in power generation and improvement of voltage profile as well as reduction of power losses. The power losses obtained in this scenario are 282.3 kW and 279.7 kVar as shown in Fig. 9, these values of power losses are 154.9 kW and 159.6 kVar lower than scenario 1. This translates to 35.43% and 36.33% reduction in active and reactive power losses when compared with scenario 1. The bus voltages recorded in this scenario are presented in Fig. 10. The voltage deviation of 0.6395 V as presented in Fig. 11, this indicates that the magnitude of voltage profile has improved by 71.837% when compared with scenario 1. The results obtained from this scenario such as power losses, voltage deviation and bus voltage profile are better than scenario 1.



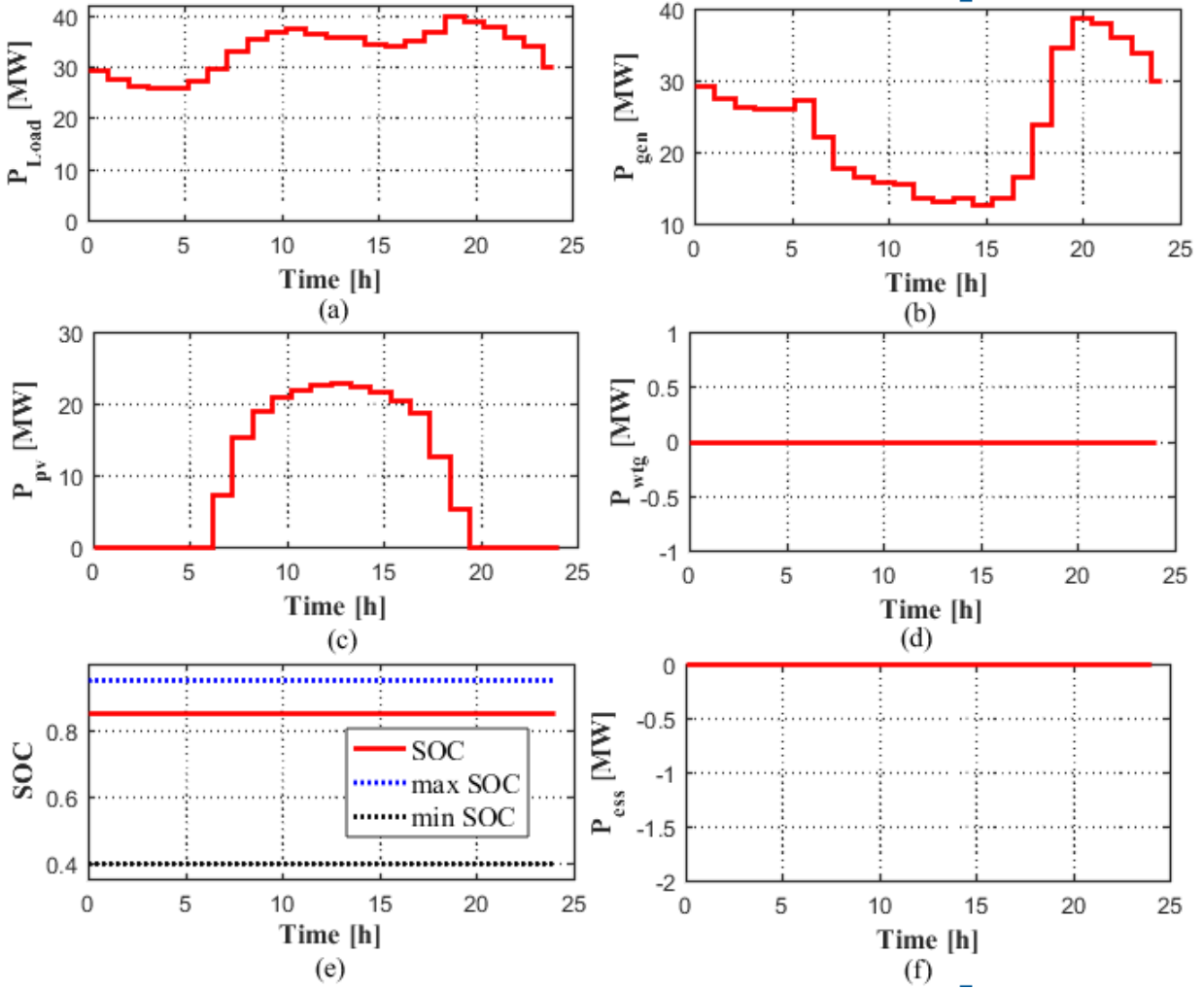


Fig. 12 Scenario 2: variation of (a) load demand, (b) power from the DG, (c) power from the PV system, (d) power from the WTG system, (e) SOC and (f) power from the ESS.

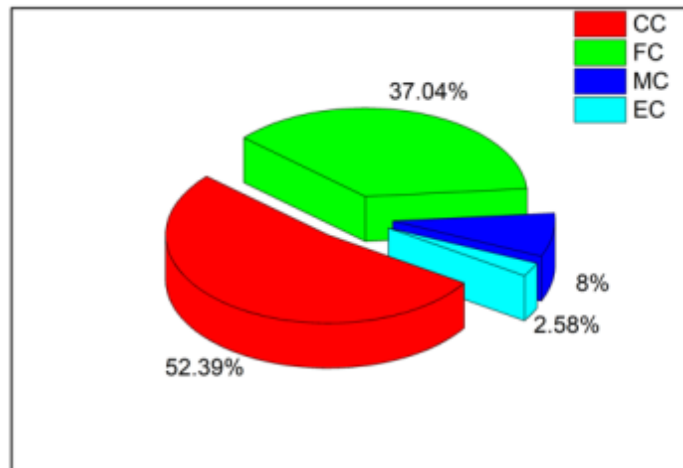


Fig. 13 Breakdown of the total annual cost for scenario 2

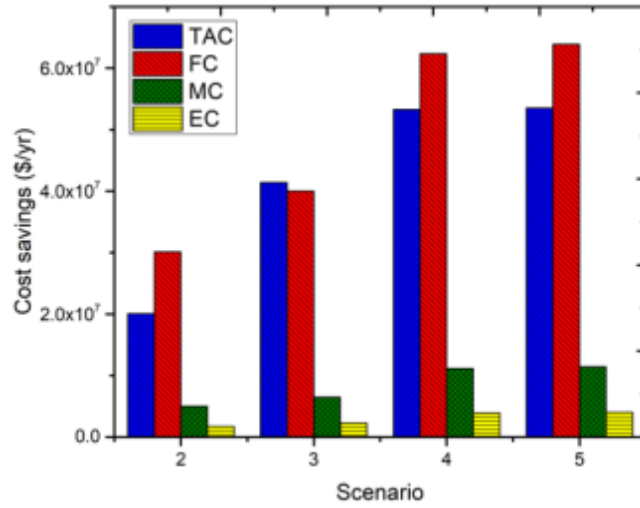


Fig. 14 Improved cost savings of the proposed microgrid system with ESS, PV and WTG

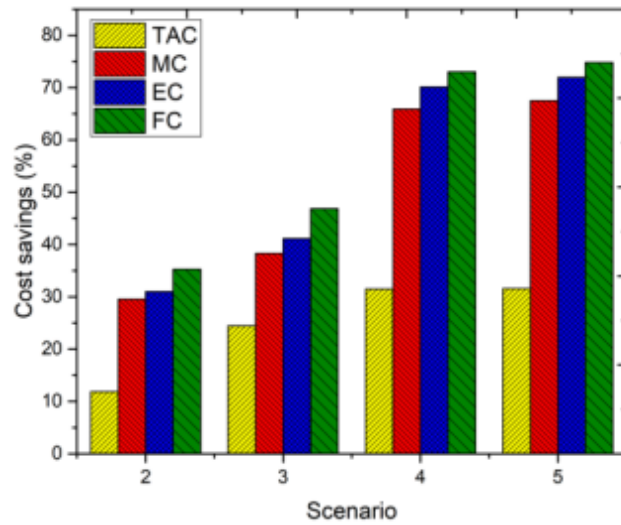


Fig. 15 Percentage of improved cost savings of the proposed microgrid system with ESS, PV and WTG

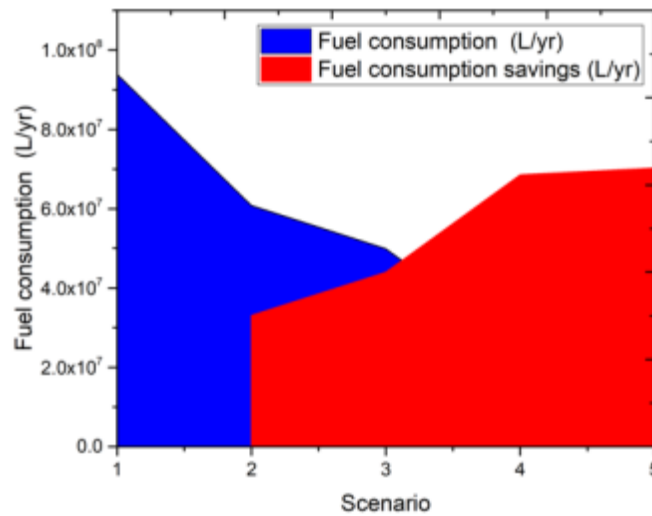


Fig. 16 Fuel consumption and savings with ESS, PV and WTG

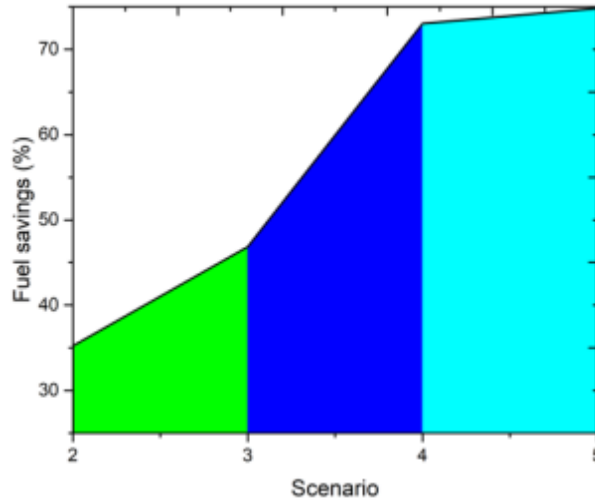


Fig. 17 Percentage of fuel consumption savings with ESS, PV and WTG

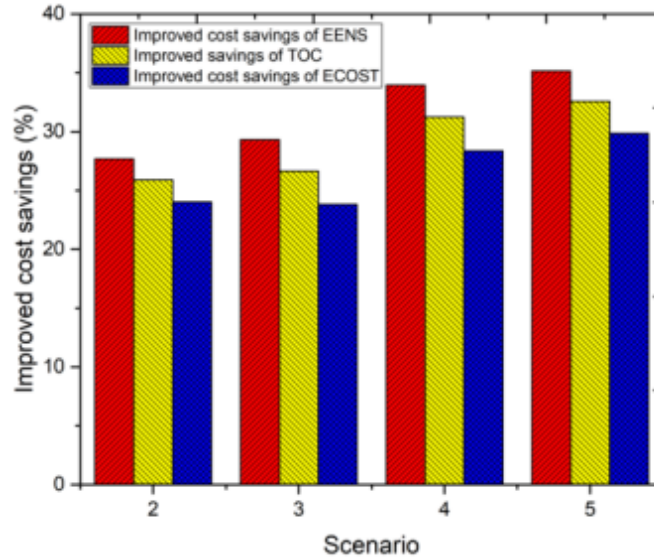


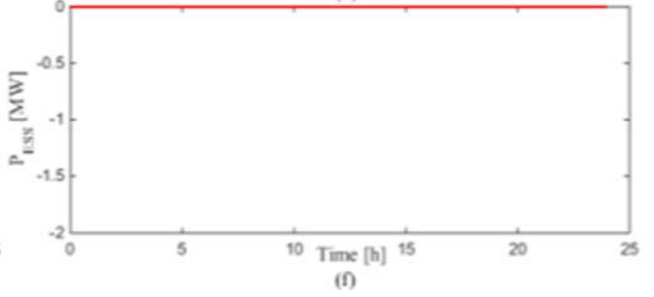
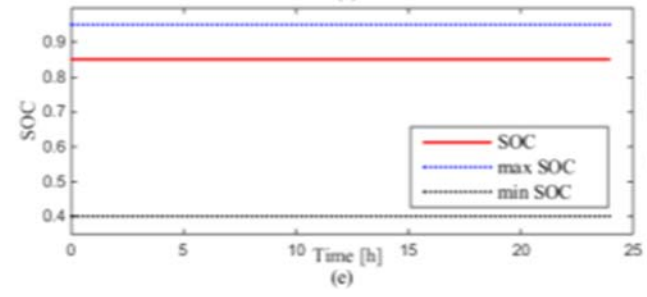
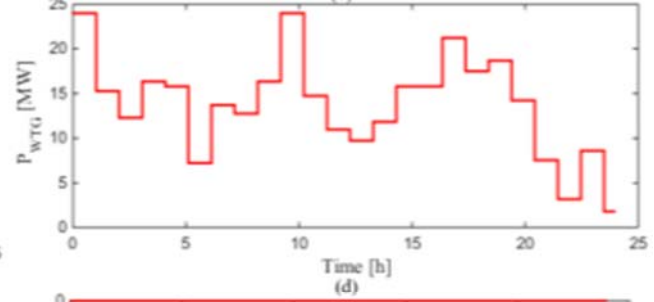
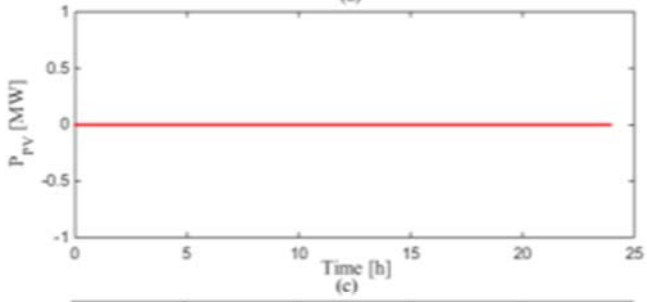
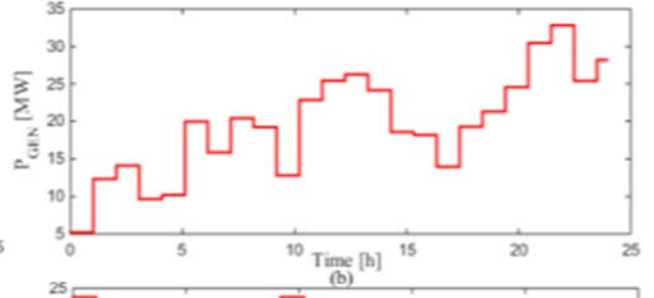
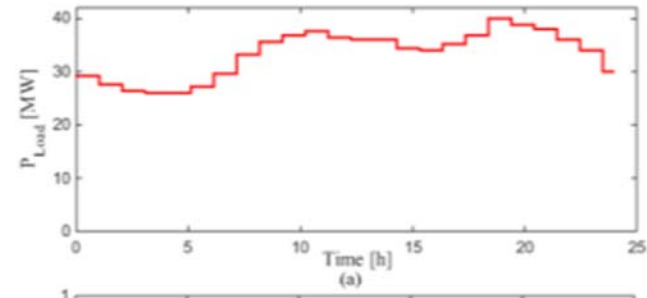
Fig. 18 Impacts of the ESS, PV and WTG on the reliability of a microgrid system

Scenario 3: DG and WTG system

The power contribution of the DG and WTG system to the entire power system is shown in Fig. 19 (a-f). The application of the WTG system has reduced the power generated by the DG by less than 50% of the installed capacity and this increased the reserve merging of the system. The composition of the TAC for this scenario is presented in Fig. 20 where CC has the largest share of 53.79% of the TAC. The system has a TAC of \$127967635/yr, CC of \$68830235/yr, FC of \$45394000/yr, MC of \$10460000/yr and EC of \$3283400/yr as shown in Fig 5 and Table 4. In this scenario, the TAC, FC, MC and EC savings have increased substantially with the utilization of the WTG system by 24.45%, 46.85%, 38.30% and 41.13% respectively as shown in Table 4 and Fig. 15. It indicates that the results further prove that the application of the WTG system in a microgrid system has enhanced the cost savings of the system. The value of CO₂ emission is 113040000 kg/yr, SO₂ is 61859 kg/yr and NO_x is 1151300 kg/yr as shown in Table 5 and Fig.

6a-c. It can be observed that GHG emissions in this scenario are lower than the first scenario due to the high degree of RETs penetration in the power system. The value of EIR in this scenario is 59% as presented in Fig. 7, and this has justified the impact of the WTG on the CO₂, NO_x and SO₂ emissions. The application of the WTG system has minimized the fuel consumption of the DG to 49884000 L/yr as shown in Table 6 and Fig. 16. This indicates that there is a 46.85% enhancement in the FC savings with the integration of the WTG system as shown in Fig 17.

The reliability performance of the system has improved significantly with the utilization of the WTG system at the various bus bars within the distribution system. The reliability indices for instance SAIFI, SAIDI, CAIDI and AENS have improved by 81.57%, 32.37%, 72.75% and 29.27% respectively. It is evident from this scenario that the reliability of the network has increased substantially with the application of the WTG in the existing traditional power system based on the value RI which is estimated to be 0.58. The penetration level of the WTG system in the base power system has a significant effect on the reliability of the network and the associated costs as shown in Table 7. Furthermore, it can be established from the results obtained in the scenario that the value of ECOST is \$545510.10 /yr, EENS is 96.851 MWh/yr and TOC is \$1078190.6/yr, respectively. The application of the WTG has increased the cost savings of ECOST, EENS and TOC by 28.808%, 29.320% and 26.635% as shown in Fig. 18. The integration of WTG into the existing distribution system reduced the active and reactive power losses to 266.4 kW and 263.5 kVar as shown in Fig. 9. With the injection of WTG into the existing distribution system, the active and reactive power losses have been reduced in this scenario by 170.8 kW and 175.8 kVar. The percentages of active and reactive power losses reduction recorded in this scenario are 39.07% and 40.02% respectively. This also affects the voltage profile at each bus as presented in Fig. 10. The voltage deviation obtained in this scenario is 0.47773 V as shown in Fig. 11. This indicates that the voltage profile of the system has significantly improved by 78.9624% with the application of WTG. The results obtained in this scenario are much better than scenarios 1 and 2 in terms of the active and reactive power losses reduction and voltage profile improvement.



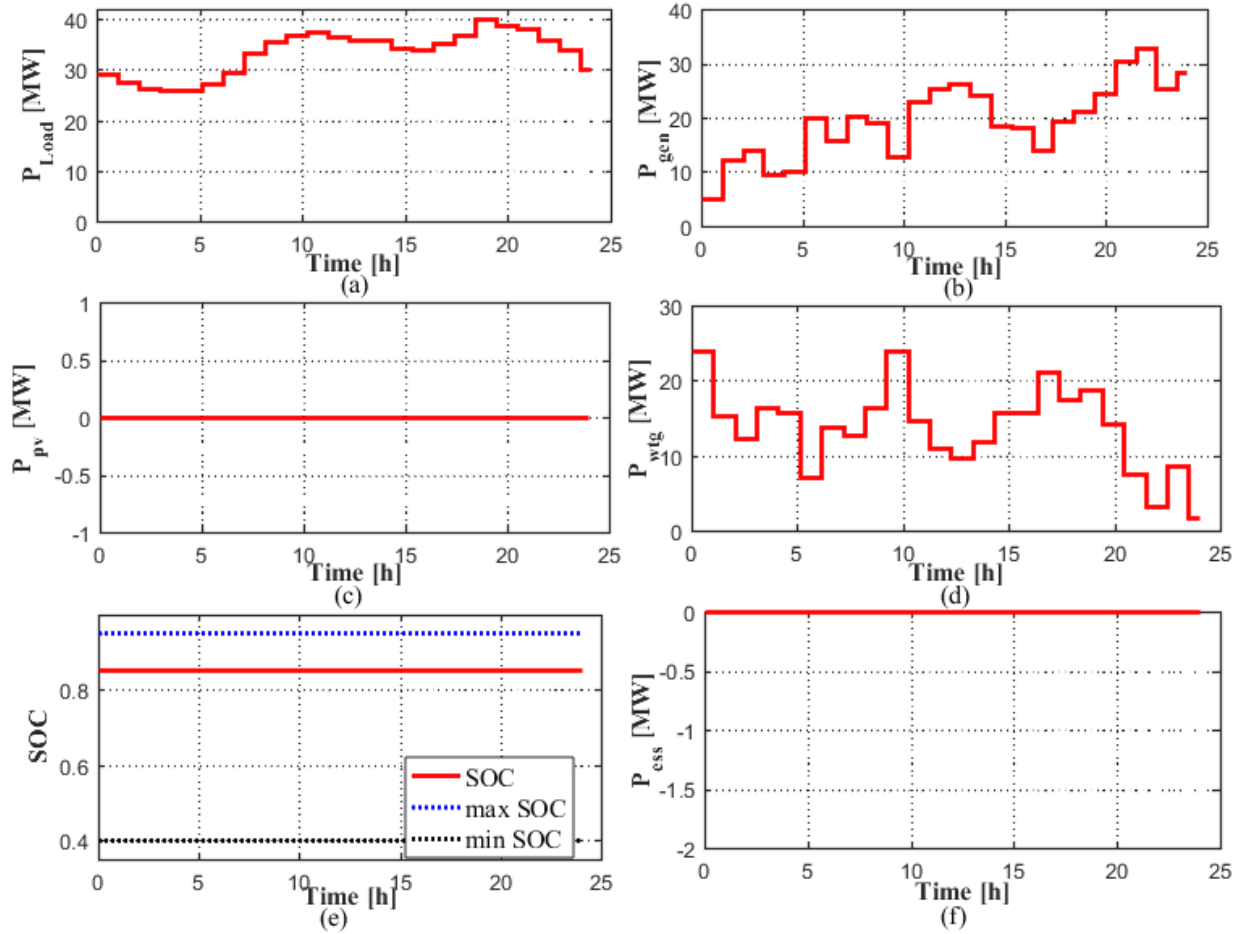


Fig. 19 Scenario 3: variation of (a) load demand, (b) power from the DG, (c) power from the PV system, (d) power from the WTG system, (e) SOC and (f) power from the ESS.

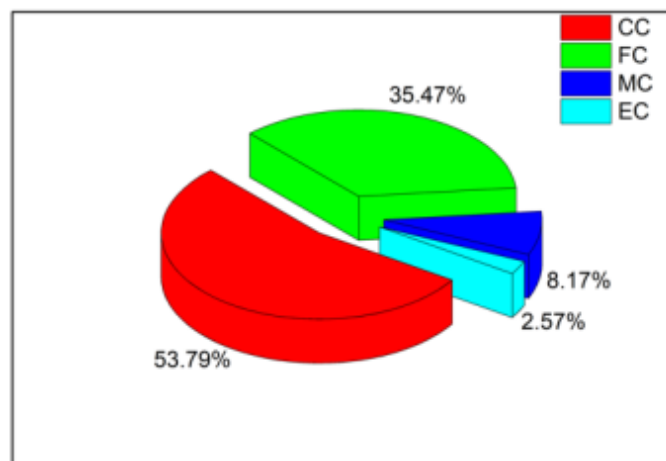


Fig. 20 Breakdown of the total annual cost for scenario 3

Scenario 4: DG, PV system and WTG system

The performance of the microgrid system has further increased by utilizing the PV and WTG systems, where the power output of the DG, PV system and WTG system are presented in Fig. 21 (a-f). This has considerably reduced the power generation of the DG by less than 60% of the installed capacity and this enhances the efficiency of the system. The breakdown of TAC for scenario 4 is presented in Fig. 22 where it is established that the CC has the highest percentage of the TAC with 73.24%. Moreover, the system has a TAC of \$116092711/yr, CC of \$85607611/yr, FC of \$ 23040000/yr, MC of \$5780300/yr and EC of \$1664800/yr as presented in Fig. 22 and Table 4. The power system has a lower value of TAC, FC, MC and EC when compared with the first, second and third scenarios due to high levels of RETs penetration. Moreover, the TAC, FC, MC and EC savings of the system with the application of the PV and WTG systems have improved by 31.46%, 73.02%, 65.90% and 70.15% respectively as presented in Table 4 and Fig.15. This indicates that the integration of the PV and WTG units into the existing power system is an important investment decision that must be based on the cost, technical and environmental criteria. As can be observed in Table 5 and Fig. 6a-c, the value of CO₂ emission is 113040000 kg/yr, SO₂ is 61859 kg/yr and NO_x is 1151300 kg/yr. The penetration level of RETs in the power system is very high; this lowers the amount of emissions from the system as presented in Fig. 14. This has justified the lower value of EIR (30%) obtained in this scenario as shown in Fig. 7. The fuel consumption in this scenario is 25319000 L/yr as presented in Table 6 and Fig. 16. This indicates that the FC savings have been improved by 73.02% as shown in Fig. 17.

The results presented in Table 7 show that the reliability of the power system improves with the utilization of the WTG system and PV system at the respective load points where the consumers are residential, commercial and industrial. The reliability indices such as SAIFI, SAIDI, CAIDI and AENS have improved by 85.84%, 35.59%, 78.02% and 34.15% with the integration of the PV and WTG into the existing distribution power system. This demonstrates that the system is more reliable than using the DG alone to fulfill the consumer's load demand. The value of RI for this scenario is 0.540 as shown in Fig. 8, this demonstrates that the integration the PV and WTG systems into the base power system have brought a considerable enhancement in the reliability of the system. Similarly, it can be seen from the results obtained in the scenario that the value of ECOST is \$512842 /yr, EENS is 90.511 MWh/yr and TOC is \$1010652.5/yr as presented in Table 7. Hence, cost savings of ECOST, EENS and TOC have increased by 31.230%, 27.990% and 33.94% respectively as shown in Fig. 18. The active and reactive power losses obtained in this scenario are 248.9 kW and 245.4 kVar as shown in Fig. 9, with a substantial reduction in power active and reactive losses when PV and WTG are integrated into the base distribution power system. This indicates that the active and reactive power losses have reduced significantly by 188.3 kW (43.07%) and 193.9 kVar (44.14%) respectively. The injection of PV and WTG at respective bus bars has improved the voltage profile of the system as shown in Fig. 10. The voltage variation obtained in this scenario is 0.2808 V as shown in Fig. 11; this has translated to a considerable improvement in the voltage profile of the network by 87.633%. This shows that indicates that the allocation of PV and WTG units in this scenario is much better than scenarios 1, 2 and 3 in terms of the voltage deviation, voltage profile improvement and active and reactive power losses reduction.

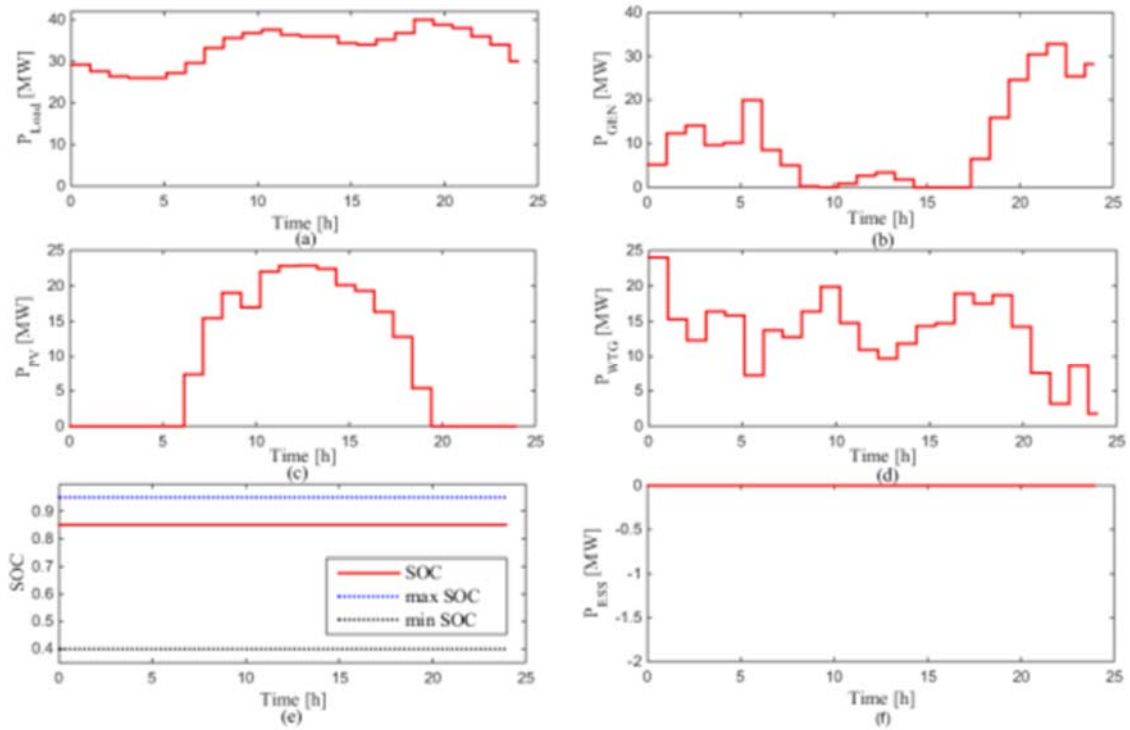


Fig. 21 Scenario 4: variation of (a) load demand, (b) power from the DG, (c) power from the PV system, (d) power from the WTG system, (e) SOC and (f) power from the ESS.

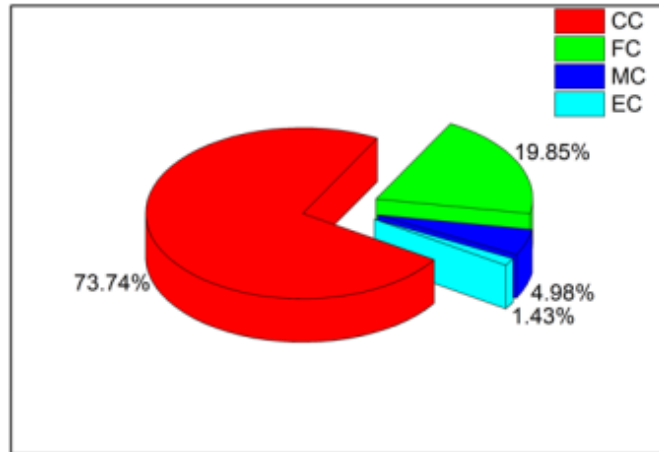


Fig. 22 Breakdown of the total annual cost for scenario 4

Scenario 5: DG, PV, WTG and ESS

The power system is running properly based on the power supply from the DG, WTG, PV and ESS as presented in Fig. 23 (a-f). The contribution of the DG to the system has considerably reduced by more than 70% due to the application of RETs and ESS in the power system. The composition of the TAC is presented in Fig. 24 where it is well established that CC has the largest percentage with 79.00% of the total annual cost. The power system has a TAC of

\$53519236/yr, CC of \$87268721/yr, FC of \$21513000/yr, MC of \$5514500/yr and EC of \$1564200/yr as presented in Fig. 5 and Table 4. The TAC, FC, MC and EC savings of the power system have been increased substantially by 31.60%, 74.81%, 67.47% and 71.95% with the PV system, WTG system and ESS as shown in Table 4 and Fig. 15. Having compared the operating cost savings of scenario 5 with other scenarios, it is well established that this scenario is the more economical viable in terms of FC, MC and EC savings than the first to fourth scenarios. Scenario 5 is the best among the five scenarios in terms of economic performance because it is estimated to have the lowest values of TAC, FC, EC and MC. The values of FC, EC and MC of the proposed microgrid system are reduced to a certain level with the application of the WTG, PV and ESS.

From the results presented in Table 5 and Fig. 6a-c, it indicates that the CO₂ emission is 53852000 kg/yr, SO₂ emission is 29469 kg/yr and NO_x emission is 548500 kg/yr respectively. The value of EIR in this scenario is 28% and it is estimated to be the lowest owing to the low consumption of diesel fuel and high level of the RETs and ESS penetration as shown in Fig. 7. This indicates that the amount of emission reduction depends on the penetration level of the RETs and ESS. Scenario 5 is the best among the five scenarios in terms of emission reduction performance owing to the fact that it emits the lowest emissions when compared with other scenarios as shown in Fig. 6a-c. The fuel consumption in this scenario is 23641000 L/yr as presented in Table 6 and Fig. 16. This has indicated that 74.81% of the fuel consumption has been saved with the application of the ESS, WTG and PV as shown in Fig. 17. The results have justified that incorporation of RETs in a power system has a considerable effect on the fuel consumption of conventional generating units. This shows that more reduction can be accomplished by increasing the capacity of the RETs and ESS.

The reliability of the distribution network has been increased substantially with the application of the WTG, PV and ESS based on the results presented in Table 7. The SAIFI, SAIDI, CAIDI and AENS for instance, have improved by 81.57%, 32.37%, 72.75% and 29.27% respectively. This indicates that the power interruption experienced by customers at the load centres has been reduced significantly in this scenario with the application of RETs and ESS. The value of RI for this scenario is 0.53 as presented in Fig. 8, this demonstrates that the power system is more reliable than using the DG to fulfill the consumer's load requirements. The value of ECOST is \$502213.9/yr, EENS is 88,855 MWh/yr and TOC is \$990916.4/yr for this scenario. The abovementioned reliability indices have been reduced with the penetration of the WTG, PV and ESS when compared with the first to fourth scenarios. This indicates that the incorporation of WTG, PV and ESS has an important influence on the improvement of the reliability of the distribution network. The cost savings of ECOST, EENS and TOC for the system have been increased by 29.856%, 35.155% and 32.573% as shown in Table 7 and Fig. 18. This further indicates that there is a substantial increase in the performance of the power system with the application of RETs. The utilization of RETs in the existing power system offers better reliability and improves the KPIs when compared with the first scenario. Hence, the power produced by the

RETs is a preferable solution to satisfy the power demand at the minimal operating costs and desired level of the reliability.

The integration of PV, WTG and ESS units into the existing distribution network reduced the active and reactive power losses to 224.4 kW and 220.4 kVar respectively. This demonstrates that the active and reactive power losses have been reduced significantly to 212.8 kW (48.67%) and 202.4 kVar (49.83%), respectively as shown in Fig. 9. The results presented in Fig. 9 show that the least value of active and reactive power losses are obtained in this scenario when compared with other scenarios. The penetration of PV, WTG and ESS units into the respective bus bars shows that the voltage profile of the system has improved considerably as presented in Fig. 10 and voltage variation of the system is 0.09174 V as presented in Fig. 11. This indicates that voltage variation has increased by 95.9601% when compared with scenario 1. The integration of PV, WTG and ESS into the existing power system is much better than scenarios 1, 2, 3 and 4 in terms of the voltage variation reduction, voltage profile improvement and active and reactive power losses reduction. The overall simulation results showed that the proposed technique is efficient in terms of reducing the active and reactive power losses, voltage deviation and improve the profile of the system.

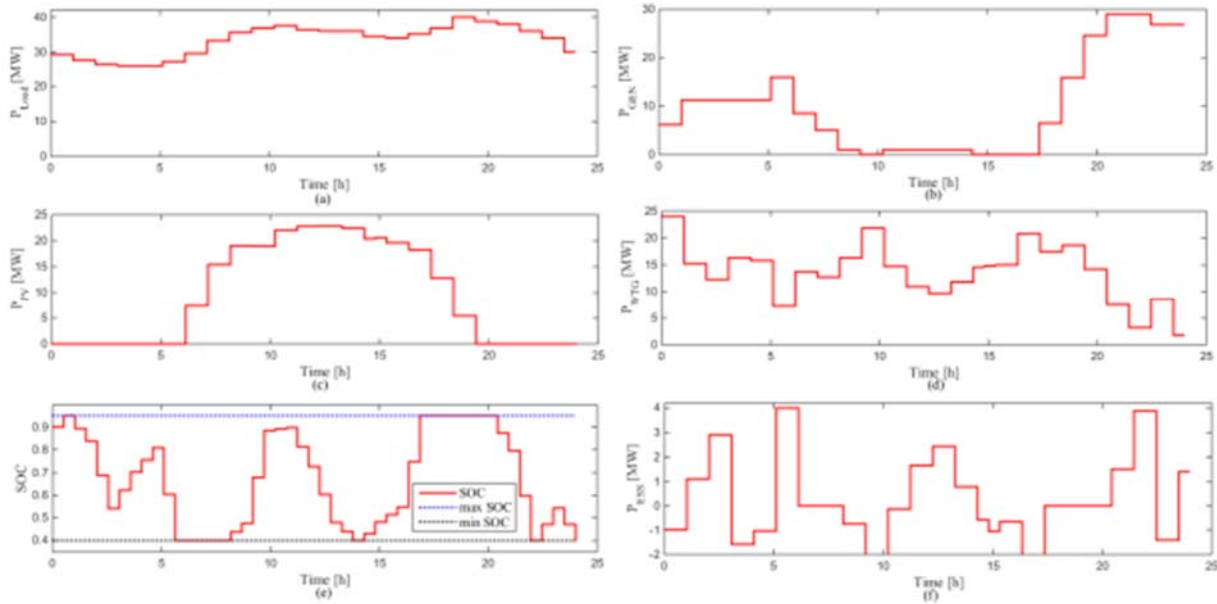


Fig. 23 Scenario 5: variation of (a) load demand, (b) power from the DG, (c) power from the PV system, (d) power from the WTG system, (e) SOC and (f) power from the ESS.

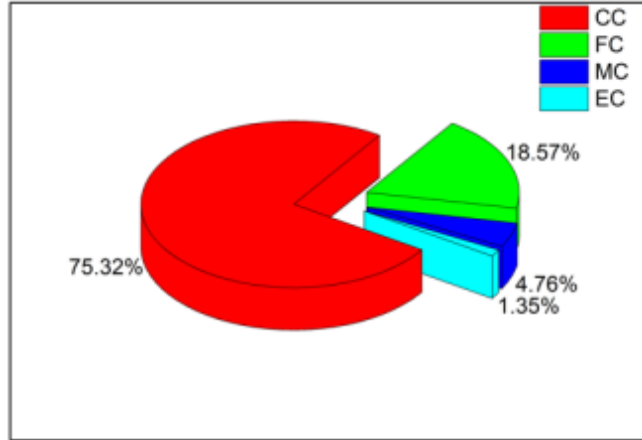


Fig. 24 Breakdown of the total annual cost for scenario 5

7. Comparing the results obtained with other existing results

The efficiency of the proposed method to obtain the best possible solution was demonstrated in the study when compared with other techniques. The robustness and proficiency of the proposed technique are spelled out by utilizing five scenarios and the results obtained from the study were compared with other methods. The novelty of the study is highlighted by comparing the most feasible scenario that operates in the similar conditions under the same or different system configurations. The comparison is based on the key performance indicator that is common to the operation of a power system as presented in Table 8. The technique presented in the present study obtains better results in term of the power loss reduction and bus voltage profile improvement when compared with references [40], [41], [53]-[55]. This shows that the novelty of the present study has been established based on the comparison with similar studies that used different heuristic algorithms and configurations. The results obtained from the can be used by the power sector stakeholders to manage the optimal operation of RETs based on their technical, economic and environmental benefits.

Table 8. Comparison of the present study other established algorithms.

Technique	Active power loss reduction (kW)	Active power loss reduction (%)	Minimum bus voltage (p.u.)
GA [53]	132.64	34.56	0.9311
Hybrid approach [54]	111.17	45.16	0.9431
Analytical [55]	111.24	45.12	-
LSF [40]	88.314	43.74	0.9134
DGPI [41]	60.5	27.96%	0.9482
Proposed method	212.8	48.67	0.98794

DGPI = Distribution generation placement index and LSF = Loss sensitivity factor

8. Conclusion

The primary goal of the power system is to satisfy load demand at the reduced power interruption and operating costs. This can be achieved with a proper economic assessment that

must be implemented with the deployment of RETs in a microgrid system. The purpose of implementing the economic analysis in the power system is to select the choice that will achieve the best reliability and economic benefits of incorporating RETs in the traditional power system. This research work investigates how RETs can be utilized by the DNOs to improve the sustainability of electric services. This research work is focused on the cost benefits of utilizing RETs for reduction of power interruption and to optimize the utilization of the distribution system effectively. The application of RETs can be used in the power system to speed up the restoration process during the power outages. A proper planning must be done by the DNOs in order to make a significant investment decision based on the costs and benefits of incorporating RETs into the power system. This paper is focused on the environmental, reliability and economic evaluation of the power system that is entirely based on the DG, ESS, PV and WTG. The objective of the work is achieved by developing a model for assessment of the effects of RETs on the performance of a power system by utilizing the reliability indices, TAC, FC, MC and EC. The wind and solar resources of De Aar that is located in the Northern Cape Province, South Africa and the sequential hourly load shape of the IEEE-RTS with the peak load of 40 MW are used in the study. It can be deduced from the outcomes of the study that the combination of the DG, RETs and ESS is more feasible when compared with an off-grid system that operates with only DG. The reliability analysis of the distribution network is implemented by considering the effects of the RI, SAIDI, SAIFI, CAIDI, EENS, AENS and ECOST under the different working modes of the DG, PV, WTG and ESS. The aforementioned key performance indicators have become a great challenge for the utilities to achieve and can effectively be reduced with the application of green technologies. The incorporation of RETs has substantial effects on the EIR, operating cost and reliability of a microgrid system. There is a considerable cost saving in the TAC, TOC, FC, EC and MC when compared with a circumstance where the power requirements are satisfied by utilizing only DG. The outcomes of this research work show that the integration of WTG and PV system into the power system is useful for both power utilities and end users due to reliability, environmental and economic benefits. The method utilized in the study can be adopted by government and international agencies as the benchmark for electrification projects in rural areas and find a permanent solution to the problem of power outages and the associated costs. Hence, the results of the five scenarios present in this work show that the PV, WTG and ESS are more economically feasible in improving the performance of the proposed power system. The application of RETs brings about a significant reduction in the FC, EC and MC on the supply side and also increases the reliability of the power system. The research work provides important information on the developed models to increase the reliability of a microgrid system at reduced operating cost. This makes the power utilities to formulate the accurate model to assess the performance of their systems. The outcomes of the study can be used by the DNOs and MGOs as the standard to improve the performance of the power system and serve as the guidelines for future research work and direction. The results obtained from the reliability assessment of the power system can be used by the DNOs as prerequisites to make the best investment decisions and operate the distribution power system optimally with minimum interruption at the load centres. The technique proposed in the study is an effective way of reducing the power losses and improving the voltage profile substantially without incurring much investment cost. The simulation results obtained from the study show the overall benefits of renewable energy technologies in the power system.

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