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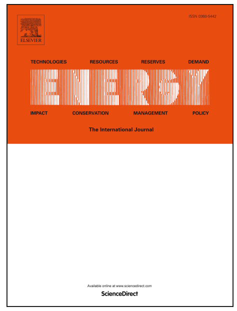

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Optimal Energy Management of a PV-WTG-BSS-DG Microgrid System

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***Abstract*:** The financial and technical advantages of renewable energy resources (RERs), coupled with their applications in the microgrid system (MGS) have considerably reduced the power demand from the utility grid. The green energy technologies (GETs) have become a potential alternative to increase energy efficiency, maximise the use of RERs and significantly reduce the operation of the diesel generator (DG). In view of this, this research work proposes an optimal power solution that comprises of the dynamic load, wind turbine generator (WTG), battery storage system (BSS), photovoltaic (PV) and DG. The energy management scheme is proposed in the study to coordinate the power sharing among the significant constituents of a MGS. The fmincon programming function is applied to explore local RERs for the benefits of customers at the demand side and to increase access to a continuous power supply. The objective of the proposed approach is to minimise the total cost (TC), minimise cost of energy (COE), maximise the benefit to cost ratio (BCR), maximise the application of RERs and minimise the operations of the DG and BSS. The variations of the power demand in spring, winter, autumn and summer are considered as the prerequisites to assess the operational efficiency of the power system. The outcomes of the research work established the fact that the proposed scheme can achieve a substantial reduction in the fuel cost (FC), maintenance cost (MC) and emission cost (EC) because the DG is only switched on when the power from RERs is not adequate to satisfy the power requirement. This indicates that the PV and WTG operate with great potentials to achieve cost savings and improve the performance of an off-grid MGS. The outcomes of this research work will provide significant information to the independent power providers (IPPs) and microgrid operators (MGOs) to make appropriate decisions while planning and designing their power systems. The results obtained from the study can be used by the government organisations as the benchmarks to improve the global power generation and reduce power crisis and subsidies on the importation of crude oil through diversification from brown energy technologies (BETs) to GETs.

Keywords: Battery storage system, diesel generator, photovoltaic, renewable energy resources, wind turbine generator.

1. Introduction

The penetration of RERs into the utility grid has improved tremendously owing to the public awareness of greenhouse gas (GHG) emissions mitigation, operation costs reduction, unpredictable load growth, regional strategic plans to curtail the global warming and plans to increase the power system quality [1]. The development of alternative renewable power sources that is highly efficient and environmentally friendly when compared to BETs has attracted the global attention due to the detrimental effects caused by GHG pollutions from the conventional power stations [2]. In view of this, RERs have the potential to provide promising solutions to the problems that are related to the fossil fuel-based power plants. Owing to the importance of a reliable power supply and rapid growth in energy demand, many countries have developed sustainable energy roadmaps to reduce the stress on the transmission and distribution systems with the application of load management policies and generation of highly efficient power from RERs [3]. The renewable energy frameworks introduced by government agencies are mainly designed to improve the security of energy supply and decrease over-reliance on fossil fuels [4], [5]. The utilisation of RERs in the conventional power system has become a promising solution to satisfy ever increasing load demand and reduction of the depletion of fossil fuels. The improvement of the power system with the idea of sustainable energy technologies and the application of state-of-the-art of the technology has made the utilities to shift from the traditional power system to the MGSs with the smart grid features [6].

The MGSs are designed nowadays to connect different distributed generation technologies with the intelligent energy management system (IEMS) for efficient operation and to optimally meet the electrical energy demands of consumers. The IEMS is equipped with the numerous information that can be utilised to analyse the importance of RERs in the power system. Generally, MGSs are low voltage distribution systems that are widely accepted for small, medium and large-scale power generation throughout the world based on the socio-economic benefits [7]. The development of a MGS enhances the flexibility of power production and its capability to intensify the performance of the power system while meeting the energy demands [8]. The electrification projects in rural areas have become a sensitive and fundamental issue owing to the steady growth in electricity demand from areas already electrified, along with the environmental concerns and support of the existing electrical infrastructures. In addition to this, the economic constraints and the depletion of fossil fuel have reduced the prospects of supplying remote areas from either the existing electrical power systems or through the deployment of additional large-scale power systems [9]. The electrification of remote areas with the proliferation of RERs has socio-economic impacts on the lives of the rural dwellers that are living in such communities [10]. The PV and WTG systems are the most promising resources that provide power supply to the nearby customers rather than the utility grid based on the techno-economic benefits. However, the intermittent nature of solar and wind resources remains a crucial challenge in the operation of the power system. The utilisation of the BSS has been considered as an effective solution to mitigate the stochastic behaviours of local RERs. The effectiveness of this solution directly depends upon the intrinsic performances of the BSS utilised in a MGS. From the electrical point of view, a good BSS should have the competency to meet the requirements of a high energy capability. Given that none of the energy storage technologies can meet these requirements while remaining cost-effective, hence, the use of a MGS that operates with the combination of numerous technologies has been projected to surmount the restrictions of a single technology [11]. Therefore, a PV-WTG-BSS-DG MGS can be used to overcome numerous problems by providing higher efficiency, greater flexibility and reduce the FC in rural communities where there is no access to electrical energy supply owing to some constraints [12], [13].

Many application tools such as HOMER, HYBRID2, SAM, INSEL, RETScreen, ORIENTE, PVSOL, RAPSIM, SOLARGIS and PVSYST have been utilised for the optimisation of off-grid and grid-connected MGSs to estimate the cost and validate the feasibility of the power systems. However, the aforementioned tools have their own drawbacks such as the utilisation of black boxes, absence of multi-objective function and cannot enable the client to naturally select suitable design apparatus. The hybridisation of a traditional power system is relatively recent, and a few numbers of research works have been implemented on the optimisation of the power systems with the proliferation of RERs at design, planning and operational levels. The previous studies that have been reviewed and presented in Table 1 demonstrate that the load variations, seasonal changes and solar and wind resources variations have become a serious challenge and an open research area that needs a public attention. Based on the aforementioned literature review, we have carried out a research work that has used the hybridisation of multiple RERs, DG and BSS to study the impacts of seasonal and load variations on the operation of the power system. Therefore, understanding of the load variations and changes in weather conditions that affect the optimum operation of a power system is a prerequisite for its detailed design and to get optimised results with cost efficiency. The results obtained from the four seasons such as summer, spring, winter and autumn are compared to analyse the effects of seasonal load variations and local resources on the optimal operation of the power system. In this research work, an optimal energy management strategy is applied to a PV-WTG-BSS-DG MGS with the goal of minimising the FC, MC, EC, TC and COE, maximising the BCR, maximising the application of PV and WTG and minimising the usage of the BSS and DG of the proposed power system based on the load profile and other operational limitations. The methodology presented in the study is used to assess the technical and financial advantages of RERs in a MGS based on the variability of seasonal power consumption. Subsequently, the nonlinear optimisation problem formulated in this research work can be effectively solved by using the fmincon solver. The energy management scheme is implemented in this research work by using the fmincon solver owing to the following advantages: it is a state of the art of the optimisation method that can be utilised to obtain the optimal solution from the MGSs, it has high proficiency to solve multi-objectives problems with numerous constraints as quickly as possible, it can handle linear and nonlinear optimisation problems with a complete limitation support and it is highly flexible to produce optimal results.

Owing to the best knowledge of the authors, a few research works have been implemented on the consolidated plan and operations optimisation for sustainable energy development as presented in this paper. This work is different from the perspectives of the work presented in the previous studies and it reveals few questions that have not been completely answered in the literature review. The outcomes of this research work can assist the IPPs to understand the concept of GETs and evaluate the benefits of wind and solar resources in their power systems. The multi-objective function utilised in the study will provide significant information to the MGOs as a measure to make the best decision for the appropriate planning and operations of their power systems. The simulated results obtained from the study can be utilised by the government agencies and multinational organisations as the standards to reduce over 1.1 billion people that are currently living on the global note without access to electricity. This will eventually intensify the capacity of the global power production through energy mix and reduce the energy crisis that many countries are currently facing.

Table 1 A literature review of the microgrid systems

Type of problems	Architecture of the power system	DG	CHP	PV	WTG	EV	BAT	TSS	PHS	IRS	Methodology	Performance indicators
OP and MOS	Grid-connected MGS [14]	✕	✕	✓	✕	✕	✕	✕	✓	✓	ANNs	AEC, PSP and LTM
OP and MOS	Off-grid power system [15]	✓	✕	✓	✕	✕	✓	✕	✕	✕	GA	COE, VC and CE
OP and MOS	Grid-connected power system [16]	✓	✓	✕	✓	✕	✓	✓	✕	✕	MINLP	TC, EC, and CPS
AP	Grid-connected MGS [17]	✕	✕	✓	✕	✕	✓	✕	✕	✕	Markov	RI
EMS	MGS [18]	✕	✕	✓	✕	✕	✕	✕	✕	✕	EFMA	OSC
OP and MOS	Smart buildings [19]	✓	✓	✕	✕	✕	✓	✓	✕	✕	MIP and GAMS	OC
OP	Standalone HES [20]	✓	✕	✓	✕	✕	✓	✕	✕	✕	HOMER	COE, EEE and NPC
OP and MOS	HES [21]	✓	✕	✓	✓	✓	✓	✕	✓	✕	IOM	COE, EE, CO_2 emissions, DF, NPC, and RF
OP and MOS	HES [22]	✓	✕	✓	✓	✕	✓	✕	✕	✕	PSO	CO_2 emission, TSC and unmet load
OP and MOS	MGS [23]	✓	✕	✓	✓	✕	✓	✕	✕	✕	MILP	OC
OP and MOS	HES [24]	✕	✕	✓	✓	✕	✓	✕	✕	✕	GA	LPSP
OP and MOS	HES [25]	✕	✕	✓	✓	✕	✓	✕	✕	✕	GA and HOMER	COE, LPSP and OC
AP	HES [26]	✕	✕	✓	✕	✕	✓	✕	✕	✕	Monte Carlo	CO_2 emission, COE, RI, and FC
OP	HES [27]	✕	✕	✓	✓	✕	✓	✕	✕	✕	HOMER and MATLAB/Simulink	NPC and COE
OP	Grid-connected MGS [28]	✕	✕	✓	✕	✕	✓	✕	✕	✕	HOMER	CO_2 emission, COE and TNPC
OP	HES [29]	✓	✕	✓	✕	✕	✓	✕	✕	✕	HOMER	CO_2 emission and TNPC
OP and MOS	HES [30]	✕	✕	✓	✓	✕	✓	✕	✕	✕	TRNSYS	RI
OP and MOS	HES [31]	✓	✕	✓	✕	✕	✕	✕	✕	✕	CSA	CO_2 emission, LPSP and TNPC
OP and MOS	Household load scheduling [32]	✕	✕	✓	✕	✕	✕	✕	✕	✕	GA	GHG emissions, COE, TC and PC
OP and EMS	HES [33]	✓	✕	✓	✕	✕	✓	✕	✕	✕	HOMER	CO_2 emission, COE, and NPC

Key: AA = Analytical problem, AEC = Annual electricity cost, ANNs= Artificial neural networks, CE = CO_2 emission, CHP = Combined heat and power, COE= Cost of energy, CPS = Cost power supply, CSA = Crow search algorithm, EC = Emission cost, EE = Excess energy, EFMA= Energy flow management algorithm, EMS = Energy management system, EV =Electric vehicle, GAMS = General algebraic modelling System, GA = Genetic algorithm, HES = Hybrid Energy system, IOM = Iterative optimisation method, IRS = Irrigation system, LTM = Life time benefits, MILP = Mixed integer linear programming, MINLP = Mixed integer non-linear programming, MIP = Mixed-integer programming, MOS = multi-objective system with hybridization of RERs, NPC = Net present cost, OC = Operation cost, OSC = Optimise self-consumption, OP = Optimisation problem, PBP = Payback period, PC = Pollution cost, PHS = Pumped storage system, PSO = Particle swarm optimisation, RI = Reliability indices, TC = Total cost, TNPC = Total net present cost, TSC= Total system cost, TSS = Thermal storage system and VC = voltage deviation.

The utilisation of the GETs will reduce annual subsidies that many countries are paying annually for the importation of petroleum products. In addition to this, the uncertainty of the crude oil prices creates a lot of economic challenges for many countries and drilling of crude oil is a dangerous process that can destroy ecosystems and causes soil degradation. Therefore, the feasible solution to increase the efficiency and optimal operation of the power system is to shift from the BETs to GETs. The significant contributions of the study to the body of knowledge are as follows:

i. A multi-objective solution is presented to solve the problem of the proposed PV, DG, WTG and BSS MGS.
ii. Application of the key operating parameter as an economic appraisal to optimize the operation of a MGS with the deployment of GETs.
iii. Formulation of a mathematical model that can be used to minimise the operations of the DG and BSS.
iv. Application of a model that can maximise the cost savings and operation of the PV and WTG units.
v. Development of a model for evaluation of the performance of a MGS based on the seasonal variations and load demand changes in the spring, winter, autumn and summer.

2. Modelling of PV-Wind-Battery-DG Microgrid System

A MGS allows the incorporation of numerous generating units as a measure to minimise the number of power outages and the operating cost of the power system [34]-[36]. It is the best option for electrification of remote communities owing to the high cost of expanding the transmission and distribution systems to the remote areas and the technical constraints that are associated with the terrains [37]. The MGOs can connect the BSS and DG to their MGSs as a measure to provide a continuous power service due to the intermittent characteristics of the wind and solar resources. This enables the MGOs to operate their power systems optimally whenever the power generated by the WTG and PV are not adequate to satisfy the consumer load demands [38]-[40].

2.1. Mathematical Model of a Microgrid System

The general structure of a MGS that comprises of the PV, WTG, DG, BSS and load is presented in Fig. 1. The major challenge of using a MGS is the proper sharing of the power among the significant components of the system. The energy management model for the overall system is obtained by utilising different components of a MGS [41]. The proposed MGS is designed in such a way that all the elements of the proposed MGS operate optimally to satisfy the electricity demand based on the constraints of the power system. The optimal operation of RERs in a MGS greatly affects the FC, MC, EC, TC, COE and BCR of the power system based on the load variations, seasonal changes and weather conditions [42]-[44]. The mathematical models that describe the characteristics of each component of a MGS are briefly presented as follows:

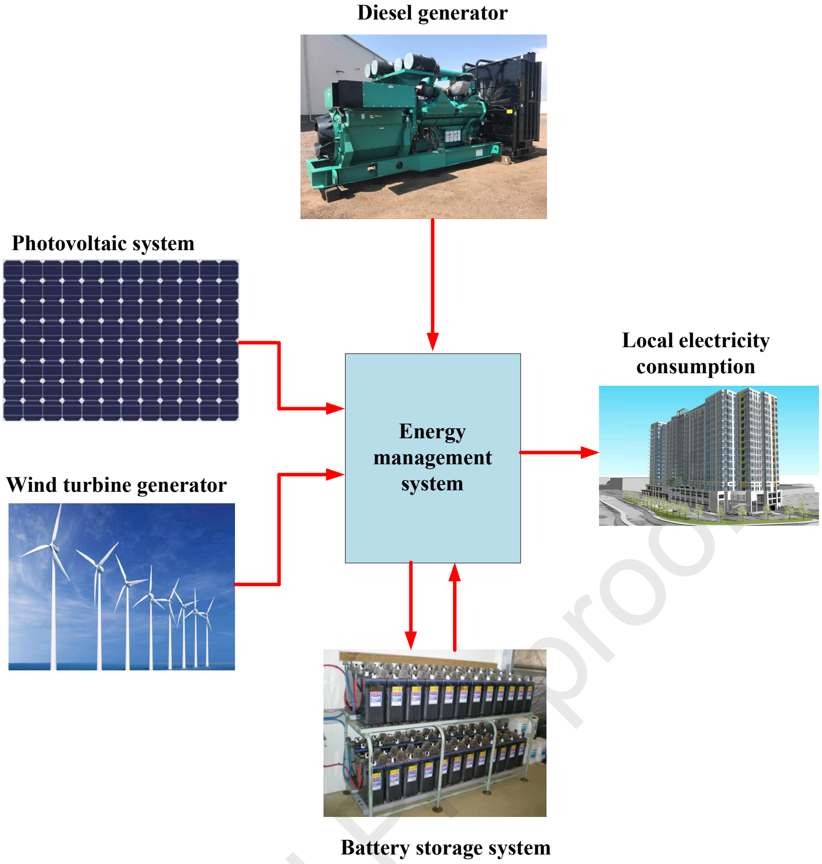

Fig. 1. Proposed electricity generation configuration for small autonomous networks.

2.1.1 Modelling of PV System

The PV system consists of a number of PV panels that are connected to converter and other hardware to generate electricity that can be used for various applications. The power output of the PV depends on the following factors, solar irradiance and efficiency and size of the PV panels [45]. The power generated by the PV system can be presented in equation (1) as [46]:

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

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

2.1.2. Modelling of WTG System

The WTG is a device that converts the kinetic energy from the wind to the electrical power by utilising the aerodynamic force from the rotor blades. The rotor of the WTG is directly coupled to the shaft and a gearbox that speed up the rotation. Hence, the rotation of the WTG via the rotor and shaft arrangement produces the electrical power that can be utilised for various applications. The power produced by the WTG can be estimated by converting the measured wind speed to the corresponding value at the hub value as expressed in equation (2) as [47]:

$$v = v_r \left(\frac{H_{hub}}{H_r} \right)^{\alpha} \tag{2}$$

where α is the power law, v_r is the wind speed at reference height (H_r) and v is the wind speed at the hub height (H_{hub}). The power generated by the WTG is expressed in equation (3) [48]:

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

where A is the rotor swept area (m^2), C_p is the coefficient performance, ρ is the air density (kg/m^3), v is the wind speed (m/s), η_g is the generator efficiency (%) and η_b is the gear/bearing efficiency (%).

2.1.3. Modelling of the Battery System

In practice, the rated voltage and rated current of a single battery are insufficient for most power smoothing applications. To overcome these limitations, strings of batteries are employed to reach a specific voltage, while several strings of BSS are connected in parallel to achieve a desired current level [49]. The optimal operating capacity of the BSS is achieved when it operates within the minimum and maximum permissible capacities stated by the manufacturer [9], [50]. The state of charge (SOC) of the BSS is presented in equation (4) as:

$$SOC^{\min} \leq (SOC\,(O) + \eta_c \sum_{t=1}^{n} P_c(t) - \eta_d \sum_{t=1}^{n} P_d(t)) \leq SOC^{\max} \tag{4}$$

where $SOC^{\max}$ and $SOC^{\min}$ are the maximum and minimum SOC of the BSS, η_c and η_d are the BSS charge efficiency and discharge efficiency and P_d is the power discharge and P_c is the power accepted by the BSS. The charged capacity of the BSS is liable to the constraint presented in equation (5) as:

$$SOC^{\min} \leq SOC\,(t) \leq SOC^{\max} \tag{5}$$

The $SOC^{\min}$ can be determined by using the depth of discharge (DOD) and $SOC^{\max}$ of the BSS [9]. Thus, the available BSS capacity always remains within its operating limits as expressed in equation (6).

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

2.1.4. Modelling of the Diesel Generator

The DGs have been used extensively for the standalone, emergency and standby power solutions because of their low initial capital costs, high efficiency, quick start-up and durability. The DGs are used by the utilities to provide the power solutions that range from continuous to prime power applications. The FC of the DG is presented in equation (7) as [51]:

$$FC = C_f \left\{ a_i P_{gen}{}^2(i,t) + b_i P_{gen}(i,t) + c_i \right\} \text{ (\$/hr)} \tag{7}$$

C_f is the fuel cost of DG ($/L), P_{gen} is the power produced by the DG (kW) and a_i, b_i and c_i are the cost coefficients of the DG. The DG is designed to operate optimally within the limits presented in equation (8) as [52], [53]:

$$P_{gen}^{\min} \leq P_{gen}(t) \leq P_{gen}^{\max} \tag{8}$$

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

3. Optimisation Model

3.1 Problem formulation

The optimisation problem that is presented in this study is aimed at finding the solution to the problem that is related to a MGS. The optimal scheduling of the DG is used in this work to minimise the TC and COE, maximise the BCR and minimise the operation of the DG and BSS while maximising the usage of the WTG and PV. The power generated from RERs is structured in such a way that it will feed the load points at a low FC, MC and EC. The diagram of the proposed MGS with the associated components and direction of power flows is shown in Fig. 2. The optimisation problem for this dispatch problem can then be formulated as follows:

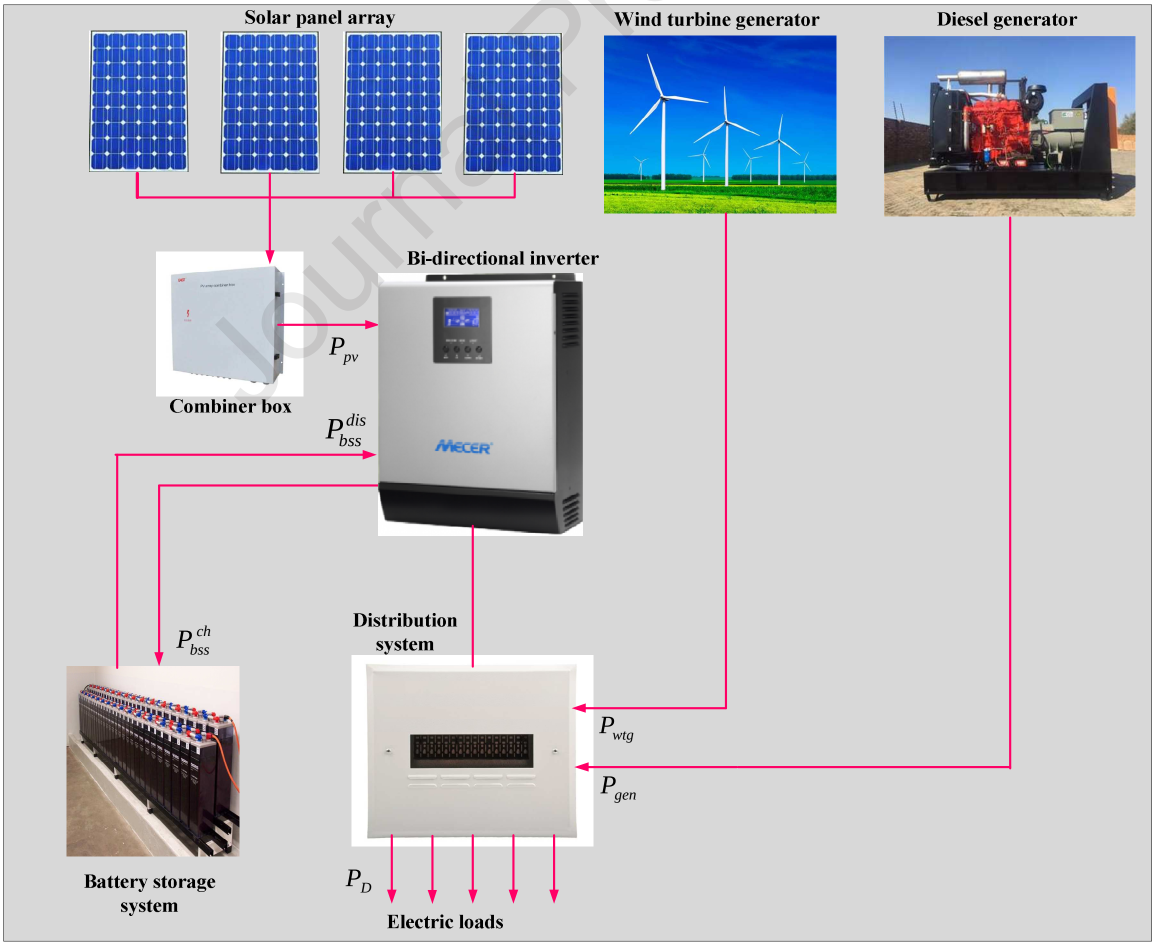

Fig. 2. Configuration of the PV-WTG-BSS-DG MGS

$$\min Ji = \min \sum_{i=1}^{n} \left\{ TC_i(t) + COE_i + P_{c,i}(t) - BCR_i(t) \right\} \tag{9}$$

where $P_{c,i}(t)$ depicts the power capacity share of the system The first, second and third components of the objective function are to minimise the TC, COE and $P_{c,i}(t)$ of the power system. The $P_{c,i}(t)$ is incorporated in the equation (9) to minimise the operation of the DG and BSS and maximise the application of the PV and WTG while the fourth component of the objective function is to maximise the BCR of the system. The total cost of the power system is presented in equation (10) as:

$$TC = \left\{ \sum_{i=1}^{n} CC_i(t) + \sum_{i=1}^{n} RC_i(t) + \sum_{i=1}^{n} FC_i(t) + \sum_{i=1}^{n} MC_i(t) + \sum_{i=1}^{n} EC_i(t) \right\} \tag{10}$$

where CC is the capital cost and RC is the replacement cost of the proposed MGS. The capital cost of a MGS can be estimated by using equation (11).

$$CC = \left\{ \begin{array}{ll} \sum_{i=1}^{n} \left(CRF_{gen,i} \eta_{gen,i} C_{gen,i} \right) & + \sum_{i=1}^{n} \left(CRF_{pv,i} \eta_{pv,i} C_{pv,i} \right) \\ + \sum_{i=1}^{n} \left(CRF_{wtg,i} \eta_{wtg,i} C_{wtg,i} \right) & + \sum_{i=1}^{n} \left(CRF_{bss,i} \eta_{bss,i} C_{bss,i} \right) \\ + \sum_{i=1}^{n} \left(CRF_{invt,i} \eta_{invt,i} C_{invt,i} \right) & \end{array} \right\} \tag{11}$$

where CRF is the recovery factor while C_{wtg}, C_{pv}, $C_{cap,ess}$, C_{gen} and C_{invt} are the initial unit costs of the WTG, PV, ESS, DG and inverter. The CRF for the proposed power system can be estimated as:

$$CRF = \frac{i(i+1)^n}{(1+i)^n - 1} \times \frac{1}{365} \tag{12}$$

where n is the life span and i is the interest rate of the component. The capital cost is a combination of initial unit cost of each component and balance of system (BOS). The BOS includes costs of installation and cost of procuring cables, fittings, and other accessories.

$$C_{x,i} = (x\% + 1) \times C_{cap,x,i} \tag{13}$$

where $C_{x,i}$ and $C_{cap,x,i}$ are the capital cost and initial unit costs of the DG, WTG, PV, BSS and inverter. While *x* is the BOS for the aforementioned components.

The replacement cost of a MGS can be estimated by using Eq. (14).

$$RC = \left\{ \begin{array}{ll} \sum_{i=1}^{n} \left(SFF_{gen,i} \eta_{gen,i} RC_{gen,i} \right) & + \sum_{i=1}^{n} \left(SFF_{pv,i} \eta_{pv,i} RC_{pv,i} \right) \\ + \sum_{i=1}^{n} \left(SFF_{wtg,i} \eta_{wtg,i} RC_{wtg,i} \right) & + \sum_{i=1}^{n} \left(SSF_{bss,i} \eta_{bss,i} RC_{bss,i} \right) \\ + \sum_{i=1}^{n} \left(SFF_{invt,i} \eta_{invt,i} RC_{invt,i} \right) & \end{array} \right\} \tag{14}$$

where $RC_{pv,i}$, $RC_{wtg,i}$, $RC_{bss,i}$, $RC_{gen,i}$ and $RC_{invt,i}$ are the unit costs of the PV, WTG, BSS, DG and inverter.

The sinking fund factor (SFF) can be expressed as:

$$SFF = \frac{i}{(1+i)^n - 1} \times \frac{1}{365} \tag{15}$$

The maintenance cost of a MGS can be estimated by using Eq. (16):

$$MC = \begin{Bmatrix} \sum_{t=1}^{n} MC_{pv} \times P_{pv}^{t}(t) + & \sum_{t=1}^{n} MC_{wtg} \times P_{wtg}^{t}(t) + \\ \sum_{t=1}^{n} MC_{bss} \times P_{bss}^{t}(t) + & \sum_{t=1}^{n} MC_{gen} \times P_{gen}^{t}(t) + \\ \sum_{t=1}^{n} MC_{invt} \times P_{invt}^{t}(t) & \end{Bmatrix} \tag{16}$$

where MC_{wtg}, MC_{pv}, MC_{bss}, MC_{gen} and MC_{gen} are the maintenance cost of the WTG, PV, BSS, DG and inverter.

The FC of the DG can be expressed as:

$$FC = \sum_{i=1}^{n} C_f (a_i + b_i P_{gen,i} + c_i P_{gen,i}^2) \tag{17}$$

The emission cost that is the summation of carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxide (NOx) emissions are expressed in equation (18) as:

$$EC = \sum_{i=1}^{n} \left(PF_i P_{gen} E_i CO_2(t) + PF_i P_{gen} E_i NO_x(t) + PF_i P_{gen} E_i SO_2(t) \right) \tag{18}$$

where PFj is the externality costs of emission, $E_i CO_2(t)$, $E_i NO_x(t)$ and $E_i SO_2(t)$ are the emission factors of the DG.

The COE can be estimated by utilizing the following expression:

$$COE = \frac{TC}{\sum_{i=1}^{n} \left\{ P_{gen,i}(t) + P_{pv,i}(t) + P_{wtg,i}(t) + P_{bss,i}(t) \right\}} \text{ (\$/kWh)} \tag{19}$$

The BCR can be used by the MGOs to make the best investment decision and determine the feasibility of a project.

$$BCR = \frac{Benefit_i}{\sum_{i=1}^{n} C_{y,i}} \tag{20}$$

where $C_{y,i}$ is the capital cost of PV, WTG, BSS, and inverter.

$$Benefit_i = \sum_{i=1}^{n} \left(TC_{base,i} - TC_{new,i} \right) \tag{21}$$

where $TC_{base,i}$ is the total cost by using DG for each season and $TC_{new,i}$ is the total cost for each season by using the MGS.

$P_{c,i}(t)$ is the power capacity share that can be used to minimise the operation of the DG and BSS and maximise the application of the PV and WTG is represented in equation (22) as follows:

$$P_{c,i}(t) = \min \sum_{i=1}^{n} \left\{ w_1 P_{gen,i}(t) - w_2 P_{pv,i}(t) - w_3 P_{wtg,i}(t) + w_4 P_{bss,i}(t) \right\} \qquad (22)$$

where $P_{gen,i}(t)$, $P_{pv,i}(t)$, $P_{wtgi}(t)$ and $P_{bss,i}(t)$ are the power outputs of DG, PV, WTG and BSS, while *wi, i* =1,2,3, and 4 are the weighted coefficients for the components of a MGS.

The first and forth components of the $P_{c,i}(t)$ are to miminise the operations of DG and BSS while the second and third components of the $P_{c,i}(t)$ are to maximise the operations of the PV and WTG.

$$w_i = \frac{P_{c,} x_i}{P_{total}}, \; w_i \geq 0, \text{ for all } i \qquad (23)$$

$$P_{total,\, i} = \sum_{i=1}^{n} \left\{ P_{c,} gen, i + P_{c,} pv, i + P_{c,} wtg, i + P_{c,} bss, i \right\} \qquad (24)$$

where $P_{c,} x_i$ is the installed capacity of each component of the system and P_{total} is the total installed capacity of the generating units (DG, PV, WTG and BSS).

The problem is solved by minimising the objective function in Eq. (9) subject to the constraints presented in Eqs. (5) and (25-27).

i. Power Balance Constraint

The load demand from consumers must satisfy the sum of power from the WTG, BSS, PV and DG. This can be expressed in equation (25) as:

$$P_{gen}(t) + P_{pv}(t) + P_{wtg}(t) - P_{bss}^{ch}(t) + P_{bss}^{dis}(k) = P_D(t) \qquad (25)$$

where P_D represents the power demand at any hour while P_{bss}^{ch} and P_{bss}^{dis} are control variables that represent charging and discharging power of the BSS at the t^{th} hour.

ii. PV and WTG Power Output Constraints

The sum of powers from the WTG and PV at the t^{th} hour for supplying the load and charging the BSS should be less than or equal to the sum of the rated power from the WTG and PV sources.

$$P_{pv}(t) + P_{wtg}(t) + P_{bss}^{ch}(t) \leq P_{pv}^{rated}(t) + P_{wtg}^{rated}(t) \qquad (26)$$

where $P_{pv}^{rated}(t)$ and $P_{wtg}^{rated}(t)$ are the rated hourly power produced from the PV and WTG based on the manufacturers' specifications.

iii. Control Variable Limits

The variable limits are the output limits of the DG, WTG and BSS at the t^{th} hour. The control variable limits of different generating sources are expressed in equation (27) as:

$$\begin{cases} P_{gen}^{\min}(t) \le P_{gen}(t) \le P_{gen}^{\max}(t), & (1 \le t \le n) \\ P_{pv}^{\min}(t) \le P_{pv}(t) \le P_{pv}^{\max}(t), & (1 \le t \le n) \\ P_{wtg}^{\min}(t) \le P_{wtg}(t) \le P_{wtg}^{\max}(t), & (1 \le t \le n) \\ P_{bss}^{ch,\min}(t) \le P_{bss}^{ch}(t) \le P_{bss}^{ch,\max}(t), & (1 \le t \le n) \\ P_{bss}^{dis,\min}(t) \le P_{bss}^{dis}(t) \le P_{bss}^{dis,\max}(t), & (1 \le t \le n) \end{cases} \tag{27}$$

iv. BSS State of Charge Limits

The BSS capacity must always remain within its operating limits at any sampling interval. This shows that the SOC of the BSS should not be greater than the maximum permissible capacity and must not be less than the minimum permissible capacity as given in (4).

4. Technical Details of a Microgrid Component

The sizes of the DG, PV, WTG and BSS are carefully chosen based on the load profile so that the proposed MGS will have the capability to satisfy the load demand. The performance of a MGS is assessed by considering a typical load profile of some consumers in Cape Town, South Africa. The technical information of the proposed MGS is presented in Table 2.

Table 2. Parameters and specifications of the proposed microgrid system [52]-[54]

Components	Technical specifications
DG	Installed capacity = 2×20 kW, Fuel cost = 0.9 $/L, Cost coefficients a = 0.0011, b = 0.1757 and c = 1.6153, Life span = 20000 hours, Maintenance cost = 0.01258 $/kWh, Initial unit cost = $2700/kW and Replacement cost = $2700/kW
WTG	Installed capacity = 1×16 kW, Rotor blade diameter = 3.2 m, Life span = 20 years, Maintenance cost = 0.08 cent/kWh, Initial unit cost = $3500/kW, Replacement cost = $3500/kW, v_{ci} = 2.5 m/s v_r = 12 m/s and v_{co} = 25 m/s Seasonal average wind speed of the site Summer = 7.14 m/s, Winter = 4.13 m/s, Spring = 4.76 m/s and Autumn = 4.20 m/s
BSS	Installed capacity = 4 kW, Life span = 5 years, Maintenance cost = 0.03 cent/kWh, Initial unit cost = $1500/unit, Replacement cost = $1500/unit, Battery discharge efficiency = 100%, Battery charge efficiency = 85% and Battery DOD = 40%
PV	Power rating = 0.2 kW, Installed capacity = 26 kW, Life span = 20 years, Maintenance cost = 0.09 cent/kWh, Initial unit cost = $4000/kW, Replacement cost = $4000/kW, Operating temperature = -40 °C to 85 °C, Open circuit voltage = 30 V, Short circuit current = 8.56 A, Maximum power voltage = 24.6 V, Maximum power current = 8.13 A and Dimensions = 1320 mm × 992 mm × 35 mm. Average solar irradiation Summer = 0.71 kWh/m^2, Winter = 0.39 kWh/m^2, Spring = 0.48 kWh/m^2 and Autumn = 0.49 kWh/m^2
Inverter	Installed capacity = 40 kW, Life span = 10 years, Maintenance cost = 0.05 cent/kWh, Initial unit cost = $2500/kW and Replacement cost = $2500/kW

5. Simulation Results and Discussions

A strategic dispatch system is designed with the combination of the DG, PV, BSS and WTG to maximise the application of solar and wind resources and minimise the operation of the DG and BSS. The proposed MGS is designed to provide electrical energy for low consumption applications based on the typical daily load data obtained from Cape Town and seasonal changes of the wind and solar resources. The load pattern indicates that the variation in the daily activities of consumers is a function of different seasons such as spring, summer, winter and autumn. The wind speed and the corresponding solar radiation of Cape Town for each season are presented in Figures 3 and 4.

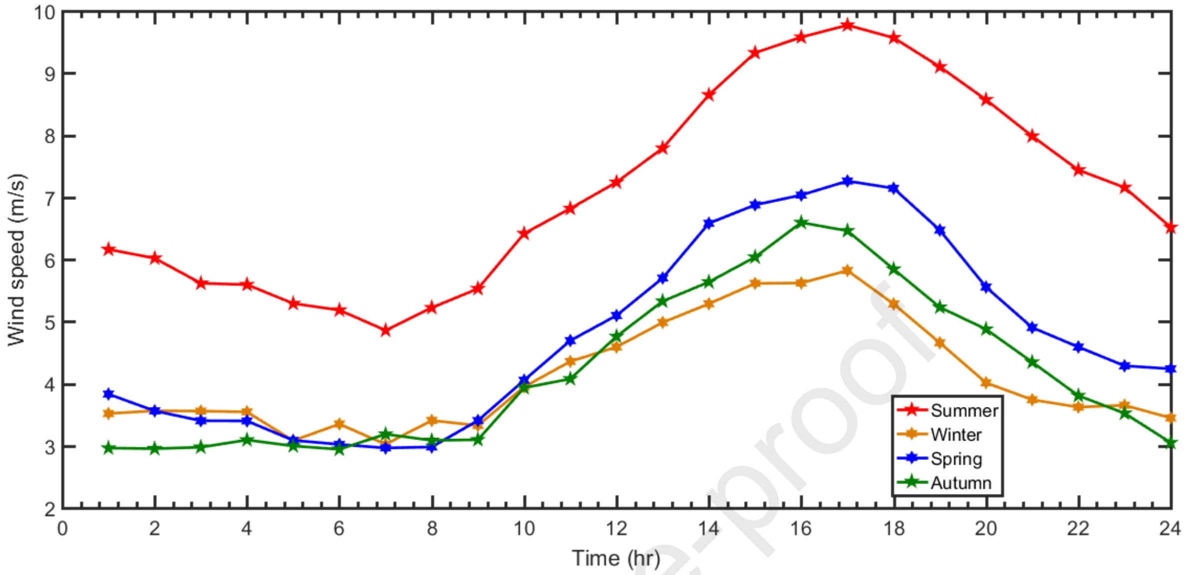

Fig. 3. Average wind speed for each season.

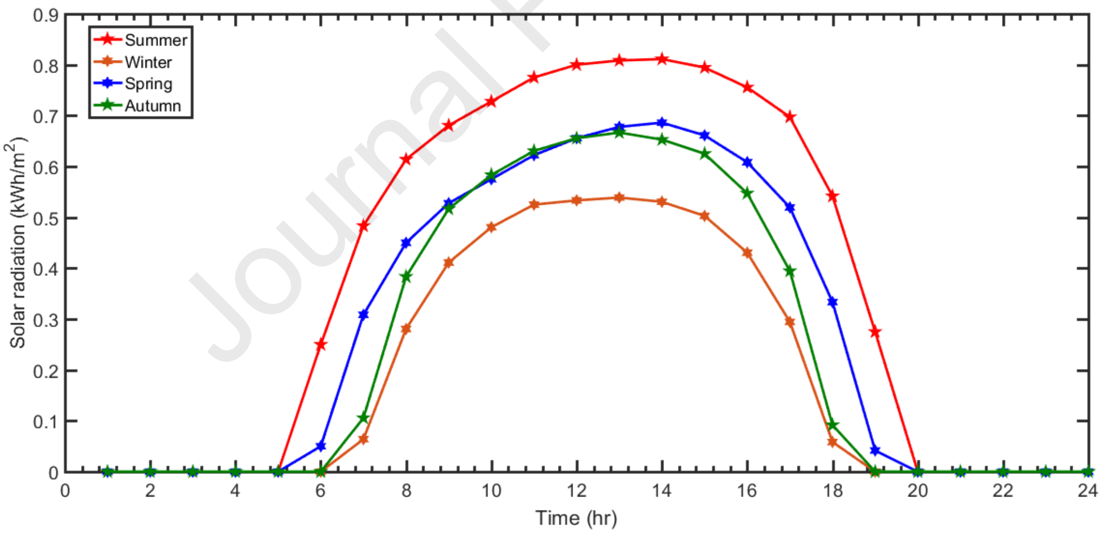

Fig. 4. Average solar radiation for each season.

Scenario 1: Load Demand Pattern in the Summer Weekday

The power demand in the summer weekday is presented in Fig. 5a while the load demand is mainly met with the combination of the DG, PV, WTG and BSS as depicted in Fig. 5(b-e). The value of SOC of the BSS based on the load demand is presented in Fig.5f. It can be substantiated from Fig. 5a that power demand is nonlinear, it is low early in the morning between 1-6 hours and has the peak period around 12-15 hours of the day. The composition of the TC during the summer weekday by using DG and MGS is presented in Fig. 6 (a-b). The FC, MC, EC, TC, COE, CO_2, NOx and SO_2 with the utilisation of the RERs in this scenario are $98.4099, $69.9901, $8.0325, $701.1516 and 0.2098 $/kWh, 1.5666kg, 0.1029kg and 0.0321 kg respectively as presented in Fig.7 and Table 3. The results show that

TC, FC, MC, EC, COE, CO_2, NOx and SO_2 savings with the following values: $353.948, $406.102, $50.3099, $22.4637, $0.106/kWh, 4.3812kg, 0.2878kg and 0.0898kg and BRC of 4.109 are achieved with the application of RERs when compared with the circumstances where the DG is utilised only to meet the power demand as shown in Figures 8-10 and Table 4. This has reduced the TC, FC, MC, EC and COE of a MGS by 33.54%, 80.494%, 41.8204%, 73.66065% and 33.56555% during the summer weekday when compared with a scenario where the DG is only used to satisfy the power requirement as shown in Fig. 11.

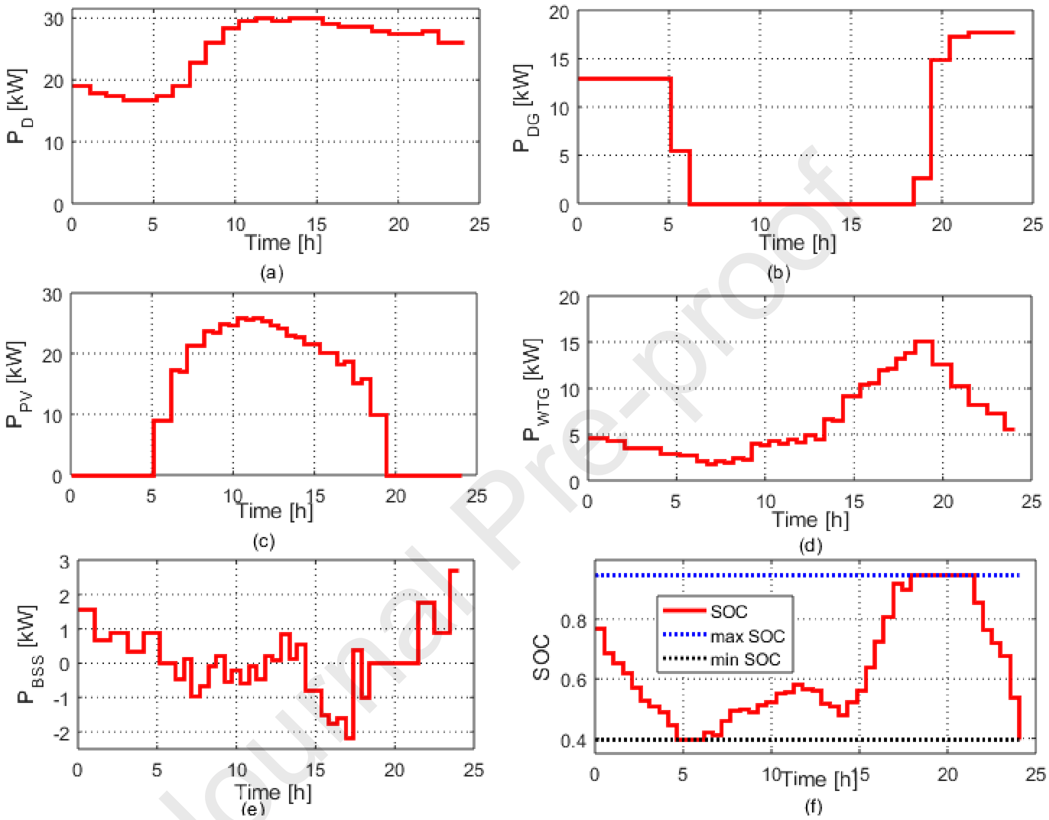

Fig. 5. Summer weekday power flow and load profile: (a) Power demand, (b) DG power output, (c) PV power output, (d) WTG power output, (e) BSS power output and (f) SOC.

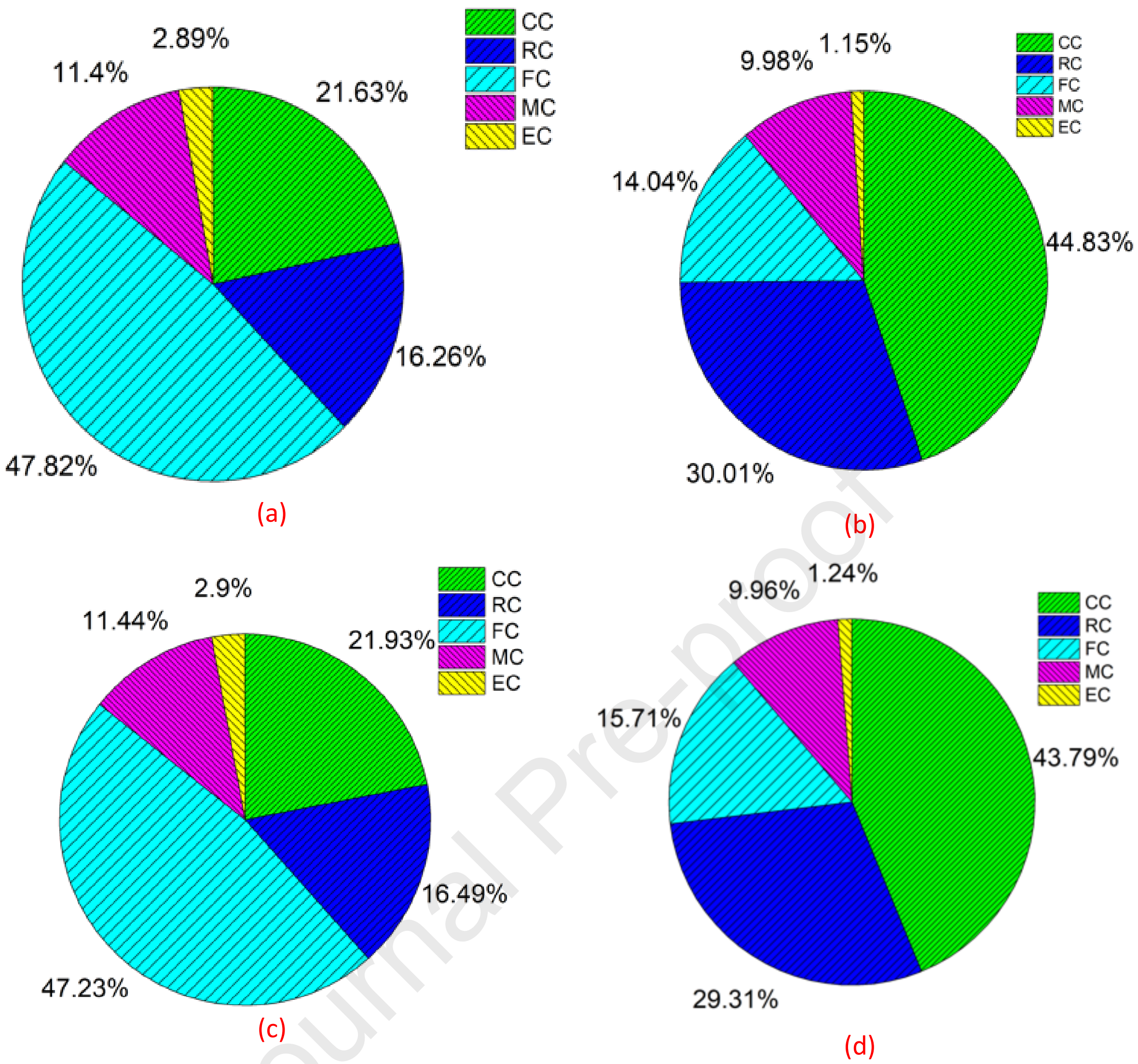

Fig. 6 Composition of total cost of the proposed power system: (a) Summer weekday DG only, (b) Summer weekday microgrid system, (c) Summer weekend DG only and (d) Summer weekend MGS

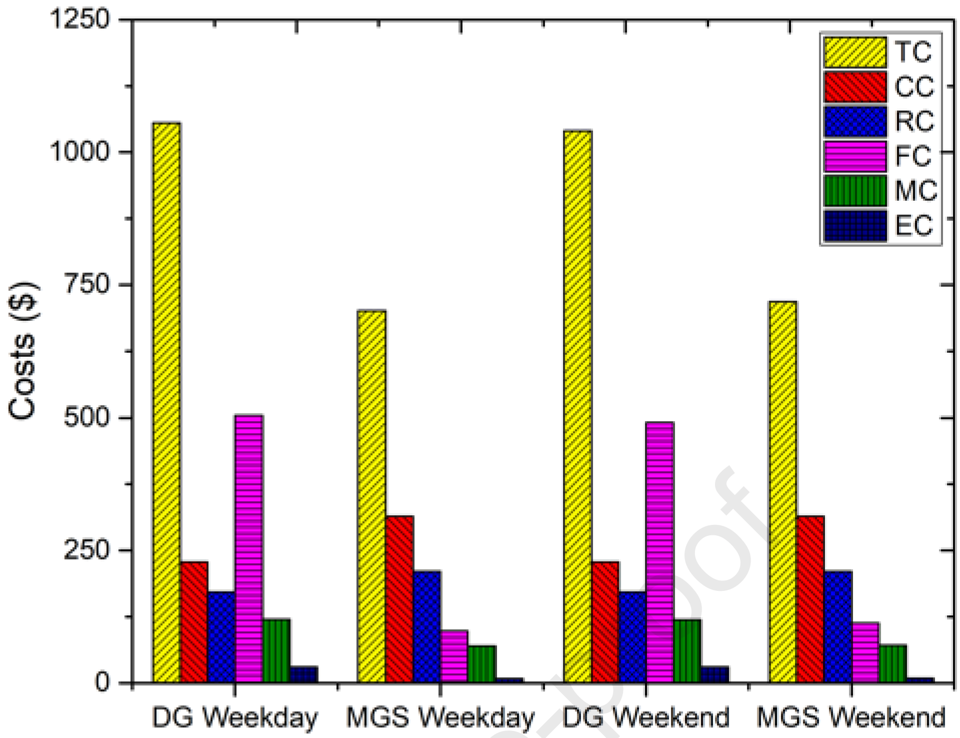

Fig. 7 Economic analysis of summer based on the seasonal variations

Table 3 Comparison of different seasons (summer and autumn)

Seasonal variation	Summer				Autumn			
	Weekday	Weekday	Weekend	Weekend	Weekday	Weekday	Weekend	Weekend
Description	DG only	Microgrid system	DG only	Microgrid system	DG only	Microgrid system	DG only	Microgrid system
CC ($)	228.2055	314.3356	228.2055	314.3356	228.2055	314.3356	228.2055	314.3356
RC ($)	171.6164	210.3836	171.6164	210.3836	171.6164	210.3836	171.6164	210.3836
FC ($)	504.512	98.4099	491.4333	112.7576	478.7043	204.2437	477.95	218.3054
MC ($)	120.3	69.9901	119.0400	71.4713	116.7	85.5675	117.24	86.3569
EC ($)	30.4962	8.0325	30.1768	8.8842	29.5836	15.2537	29.7205	15.4971
TC ($)	1055.1	701.1516	1040.5	717.8323	1024.8	829.7841	1024.7	844.8786
Total benefit ($)	-	353.9484	-	322.6677	-	195.0159	-	179.8214
COE ($/kWh)	0.3158	0.2098	0.3147	0.2171	0.3161	0.256	0.3147	0.2594
CO_2 (kg)	5.9478	1.5666	5.8855	1.7327	5.7698	2.975	5.7965	3.0225
NOx (kg)	0.3907	0.1029	0.3866	0.1139	0.379	0.1954	0.3808	0.1985
SO_2 (kg)	0.1219	0.0321	0.1206	0.0355	0.1182	0.061	0.118	0.0619

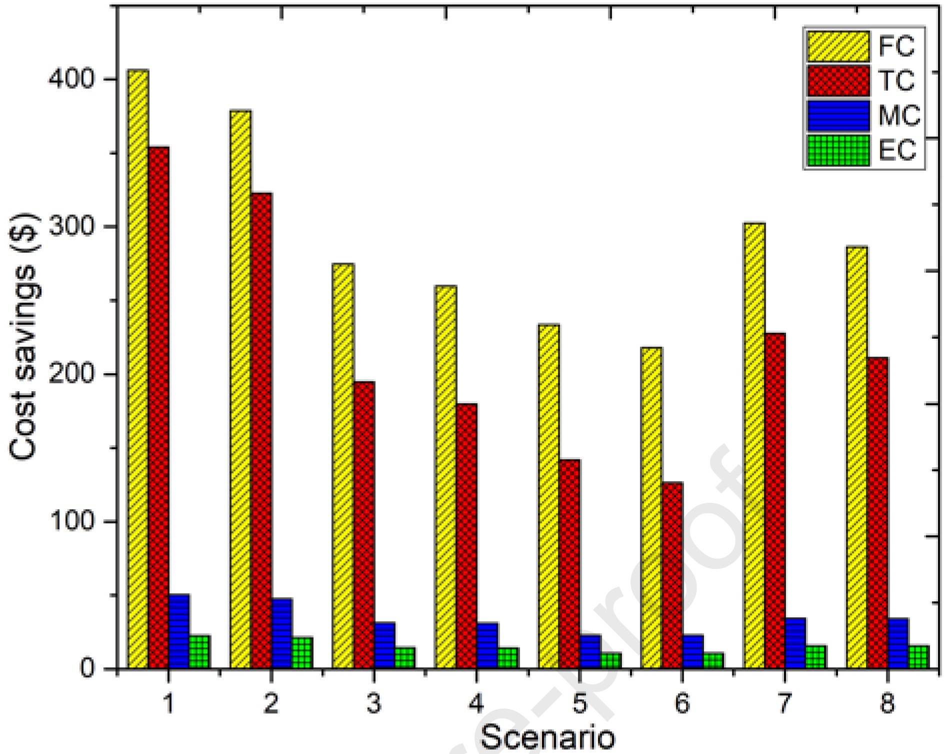

Fig. 8 Cost savings with the application of RERs

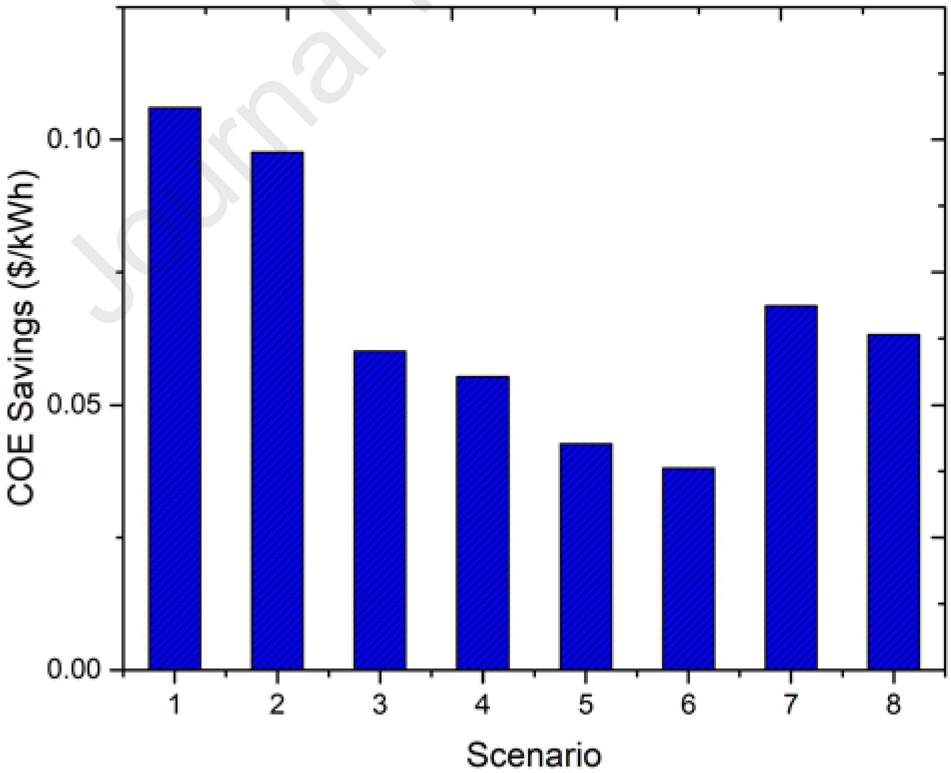

Fig. 9 COE savings with the application of RERs

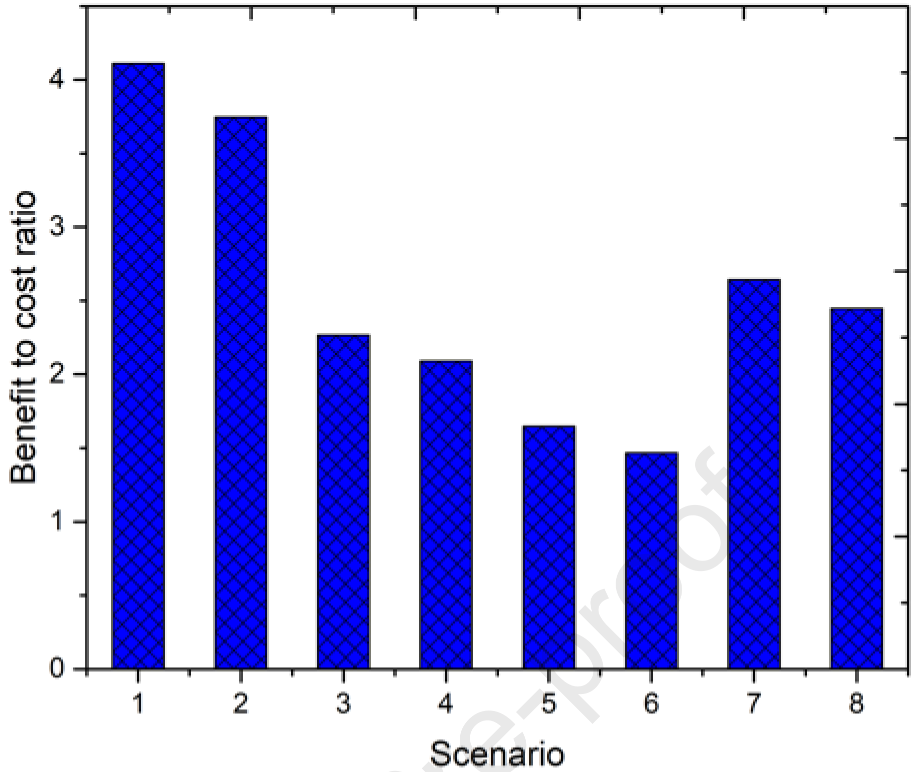

Fig. 10 BCR with the application of RERs

Table 4 Cost savings based on seasonal variation

Seasonal variation	Summer		Autumn		Winter		Spring	
	Weekday	Weekend	Weekday	weekend	Weekday	Weekend	Weekday	weekend
Scenario	1	2	3	4	5	6	7	8
TC savings ($)	353.948	322.6677	195.016	179.821	141.913	126.421	227.438	210.867
TC savings (%)	33.546	31.011	19.030	17.549	13.546	12.127	21.731	20.138
BRC	4.109	3.746	2.264	2.088	1.648	1.468	2.641	2.448
FC savings ($)	406.102	378.6757	274.461	259.645	233.222	217.732	302.282	286.186
FC savings (%)	80.4940	77.05536	57.33406	54.32464	46.83818	44.17285	60.82114	57.61352
MC savings ($)	50.3099	47.5687	31.1325	30.8831	22.8149	22.8149	34.3284	33.9852
MC savings (%)	41.8204	39.96027	26.67738	26.34178	19.08877	19.09836	28.72189	28.29271
EC savings ($)	22.4637	21.2926	14.3299	14.2234	10.7451	10.7451	15.766	15.6196
EC savings (%)	73.66065	70.5595	48.43866	47.8572	35.46413	35.48193	52.03558	51.29488
COE savings ($/kWh)	0.106	0.0976	0.0601	0.0553	0.0427	0.0381	0.0686	0.0632
COE savings (%)	33.56555	31.01366	19.01297	17.57229	13.53407	12.12603	21.75706	20.14022
CO_2 reduction (kg)	4.3812	4.1528	2.7948	2.774	2.0957	2.0957	3.075	3.075
NOx reduction (kg)	0.2878	0.2727	0.1836	0.1823	0.1377	0.1377	0.202	0.2001
SO_2 reduction (kg)	0.0898	0.0851	0.0572	0.0561	0.043	0.0429	0.063	0.0624

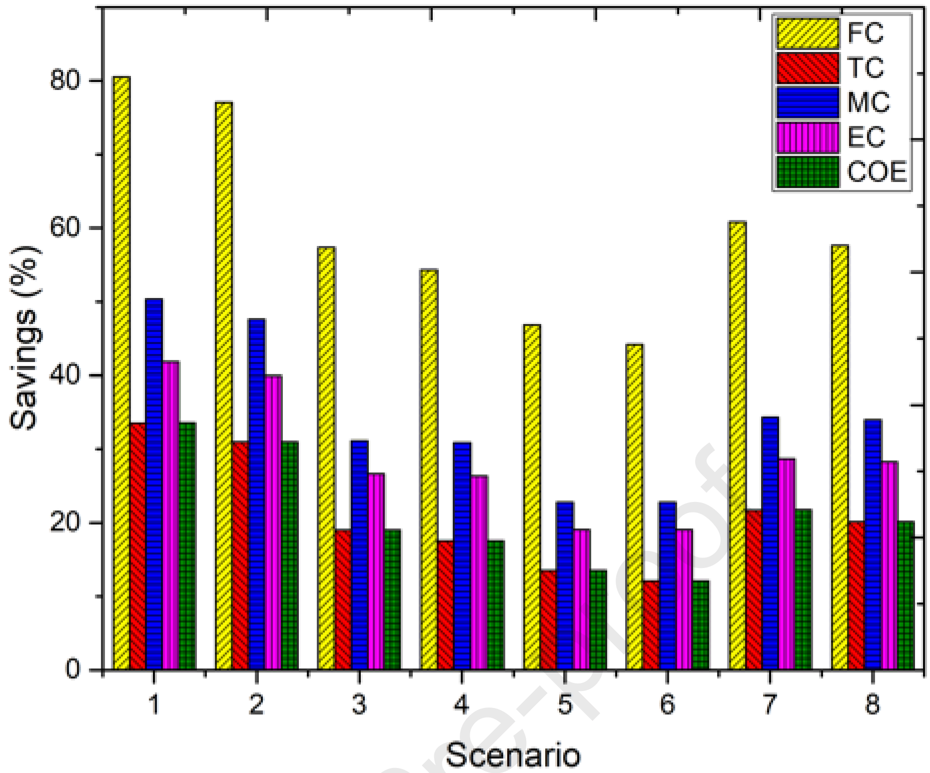

Fig. 11 Percentage savings with the application of RERs

Scenario 2: Load Demand Pattern in the Summer Weekend

The load demand in the summer weekend is satisfied with the combination of the DG, PV, WTG and BSS with their respective power outputs as presented in Fig. 12 (a-e) and SOC is presented in Fig. 12f. It is seen that the operation of the DG has been reduced significantly in the summer weekend with the combination of RERs. The composition of the TC during the summer weekend by using DG and MGS is presented in Fig. 6 (c-d). The FC, MC, EC, TC, COE, CO_2, NOx and SO_2 with the utilisation of the RERs in this scenario are $112.7576, $71.4713, $8.8842, $717.8323, 0.2171 $/kWh, 1.7327kg, 0.1139kg and 0.0355kg as presented in Fig. 7 and Table 3. This translates to FC, MC, EC, TC, COE, CO_2, NOx and SO_2 savings of $378.6757, $47.5687, $21.2926, $322.667, $0.0976/kWh, 4.1528 kg, 0.2727kg, 0.0851 kg and BCR of 3.746 as presented in Figures 8-10 and Table 4. The TC, FC, MC, EC and COE in the summer weekend have been considerably reduced by 31.011%, 77.05536%, 39.96027%, 70.5595% and 31.01366% as shown in Fig. 11 when compared with a situation where the DG is only used to meet the load demand. This shows that the operation of the DG has been minimised while the utilisation of the PV and WTG has been maximised. Since the TC and COE are 2.32% and 3.36% are higher in the summer weekend than the summer weekday owing to the load demand pattern of the consumers. This demonstrates that the TC and COE savings in the summer weekday are 8.84% and 7.92% more than the summer weekend. This indicates that the proposed MGS accomplishes a better outcome with the utilisation of GETs which shows that load dynamics and seasonal variations have an imperative effect on the TC and COE of a MGS.

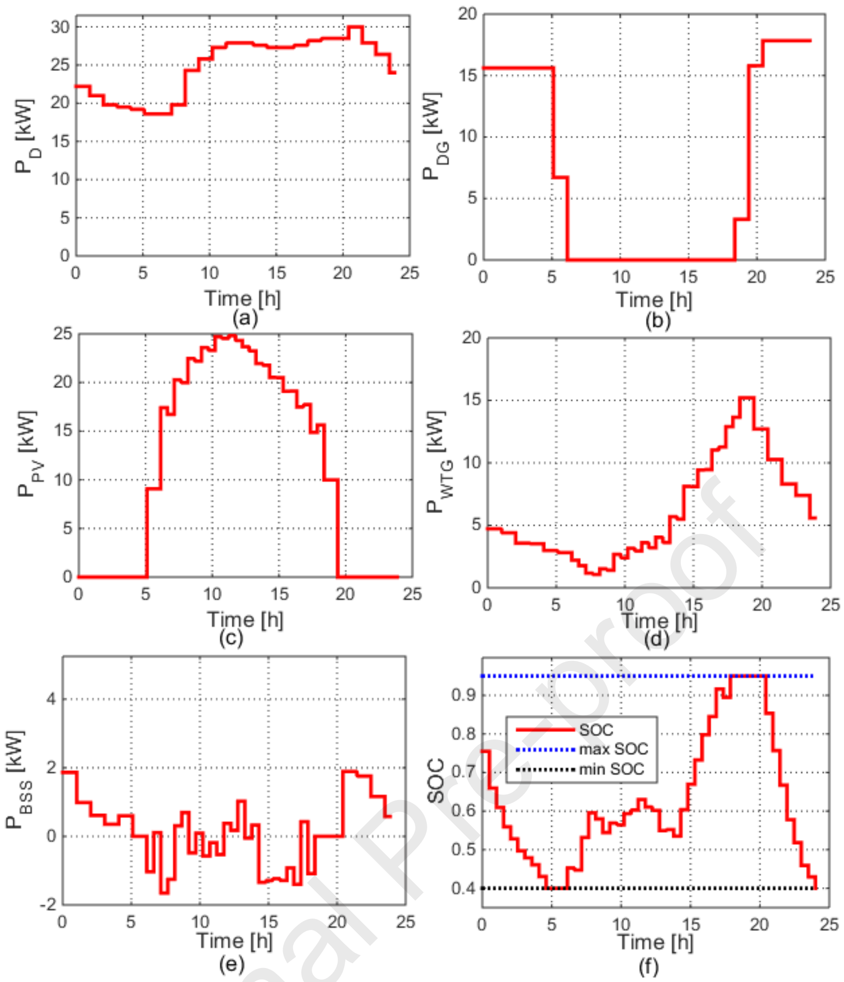

Fig. 12. Summer weekend power flow and load profile: (a) Power demand, (b) DG power output, (c) PV power output, (d) WTG power output, (e) BSS power output and (f) SOC.

Scenario 3: Load Demand Pattern in the Autumn Weekday

The load demand in the autumn weekday is met by the DG, PV, WTG and BSS, provided the generating units work within the manufacturers' operating limits to satisfy the load demand as shown in Fig. 13 (a-e) and the value of SOC is presented in Fig. 13f. The PV system has several operating hours in the summer than autumn and this indicates that the PV system supplies more power in the summer than autumn. Apart from this, the DG is switched-off earlier and switched-on later in the summer than in the autumn. The composition of the TC during the autumn weekday by using DG and MGS is presented in Fig. 14 (a-b). The values of FC, MC, EC, TC, COE, CO_2, NOx and SO_2 in the autumn weekday are $204.2437, $85.5675, $15.2537, $829.7841, 0.256 $/kWh, 2.975kg, 0.9154kg and 0.061kg as shown in Table 3 and Fig. 15. This translates to TC, FC, MC, EC, COE, CO_2, NOx and SO_2 savings of $195.016, $274.461, $31.1325, $0.061, $0.235/kWh, 2.0957kg, 0.1377kg and 0.043kg and BCR of 2.264 as shown Figures 8-10 and Table 4 when compared with a situation where the DG is used alone. It can be established from Fig. 11 that the values of TC, FC, MC, EC and COE have reduced considerably by 19.03%, 57.334%, 26.67738%, 48.43866% and 19.013% with the application of MGS. Moreover, the values of TC and COE in the autumn weekday are 15.50% and 18.05% more than summer weekday by using MGS due to seasonal variations and periodic change in load profile. This demonstrates that the TC and COE savings in summer weekday are 44.90% and 43.30% more than an autumn weekday.

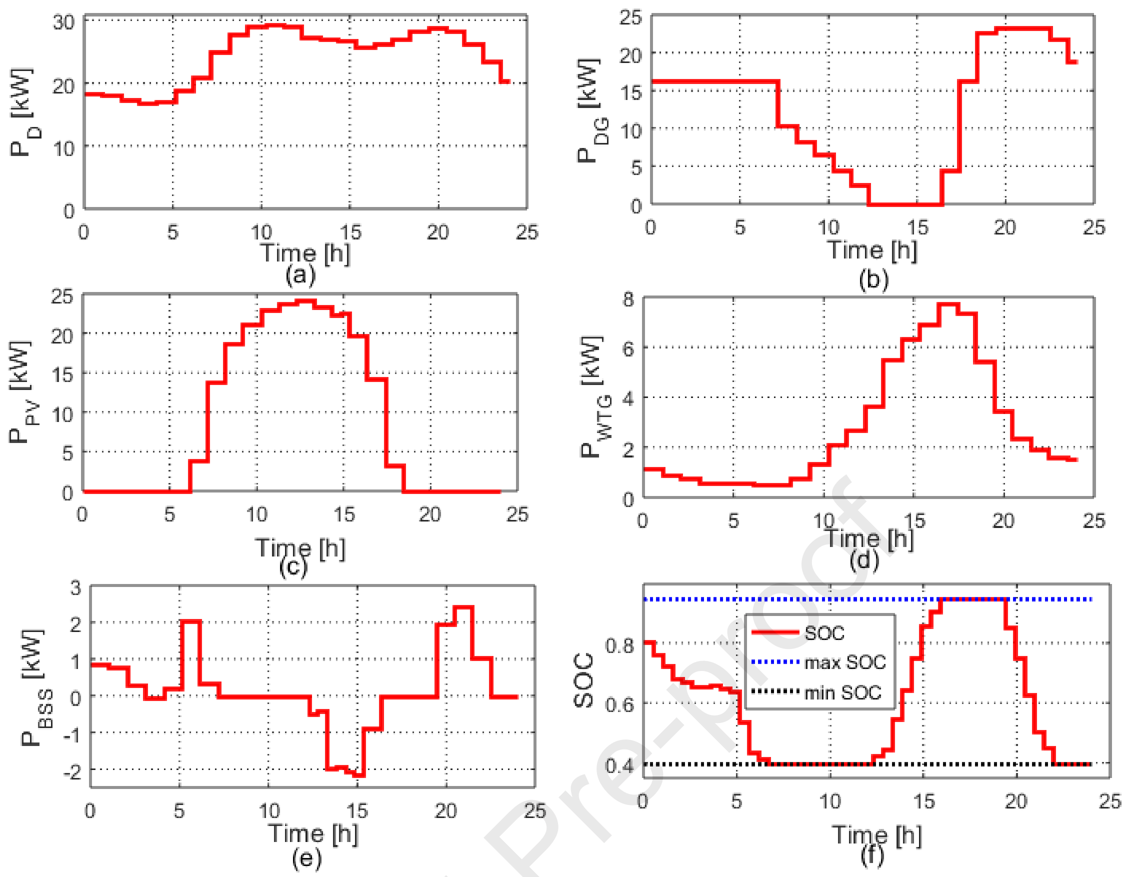

Fig. 13. Autumn weekday power flow and load profile: (a) Power demand, (b) DG power output, (c) PV power output, (d) WTG power output, (e) BSS power output and (f) SOC.

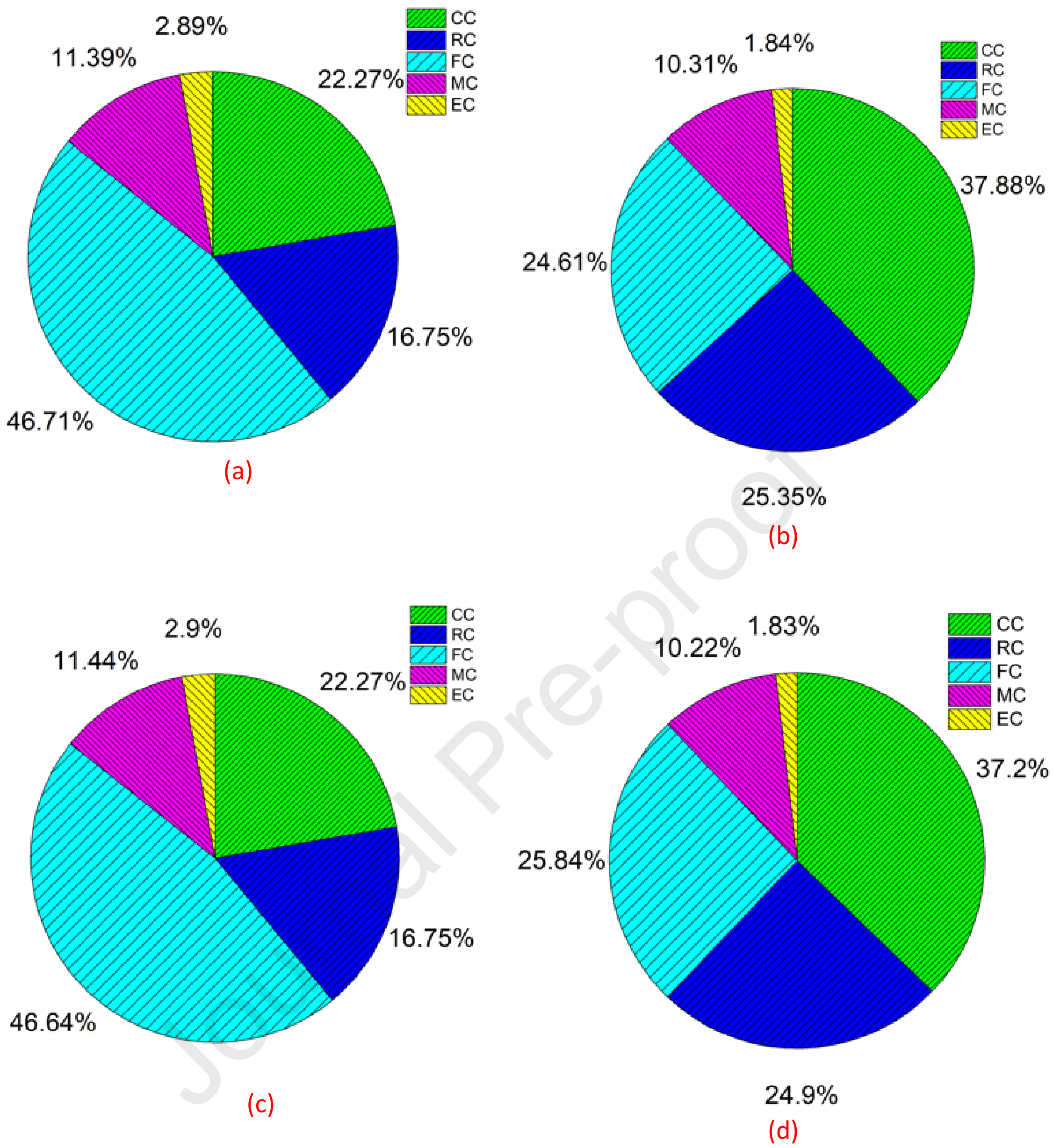

Fig. 14 Composition of total cost of the proposed power system: (a) Autumn weekday DG only, (b) Autumn weekday microgrid system, (c) Autumn weekend DG only and (d) Autumn weekend MGS.

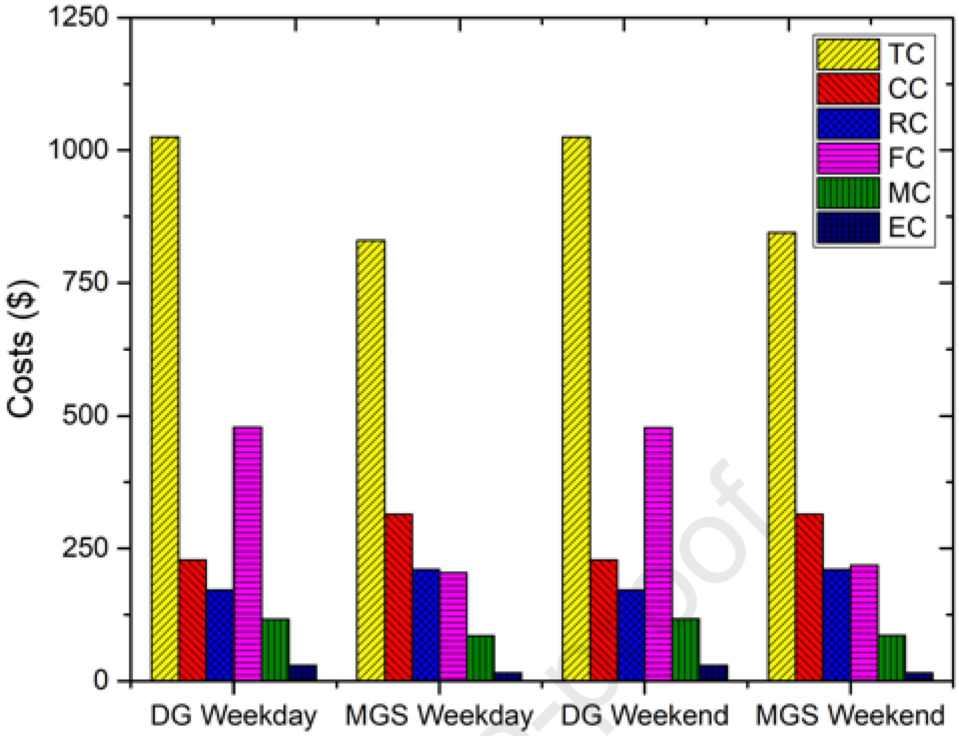

Fig. 15 Economic analysis of autumn based on the seasonal variations

Scenario 4: Load Demand Pattern in the Autumn Weekend

The power demand during the autumn weekend and the power output of each component of the proposed MGS is presented in Fig. 16 (a-e). The electricity production as presented in Fig. 16 (a-e) shows that the power output of the components of the power system is seasonal and depends on the load variations. The BSS can be charged with the combined operation of the WTG and PV and the corresponding SOC of the BSS is presented in Fig. 16f. The composition of the TC during the summer weekend by using DG and MGS is presented in Fig. 14 (c-d). The FC, MC, EC, TC, COE, CO_2, NOx and SO_2 by using the MGS to meet the load demand in this scenario are \$218.3054, \$86.3569, \$15.4971, \$844.8784 and 0.2594 \$/kWh, 3.0225kg, 0.1985kg and 0.0619kg as presented in Table 3 and Fig.15. The respective TC, FC, MC, EC, COE, CO_2, NOx and SO_2 savings are \$179.821, \$259.645, \$30.8831, \$14.2234, \$0.0553/kWh, 2.7948kg, 0.1836kg and 0.0572kg as well as BCR of 2.088 as shown in Figures 8-10 and Table 4. This shows that 17.549%, 54.32464%, 26.34178%, 47.8572% and 17.5722% of TC, FC, MC, EC and COE savings are achieved in this scenario as presented in Fig. 11. The scheduled operation of the DG reduces the TC, FC, MC, EC and COE and maximises the usage of PV and WTG. Moreover, there is a reduction in the TC and COE savings when compared scenarios 1, 2 and 3, this implies that the TC and COE in the autumn weekend are 1.79% and 1.310% higher when compared with the autumn weekday with the application of MGS. The TC and COE savings obtained in the autumn weekday are 7.79% and 7.87% more than the one obtained in autumn weekend.

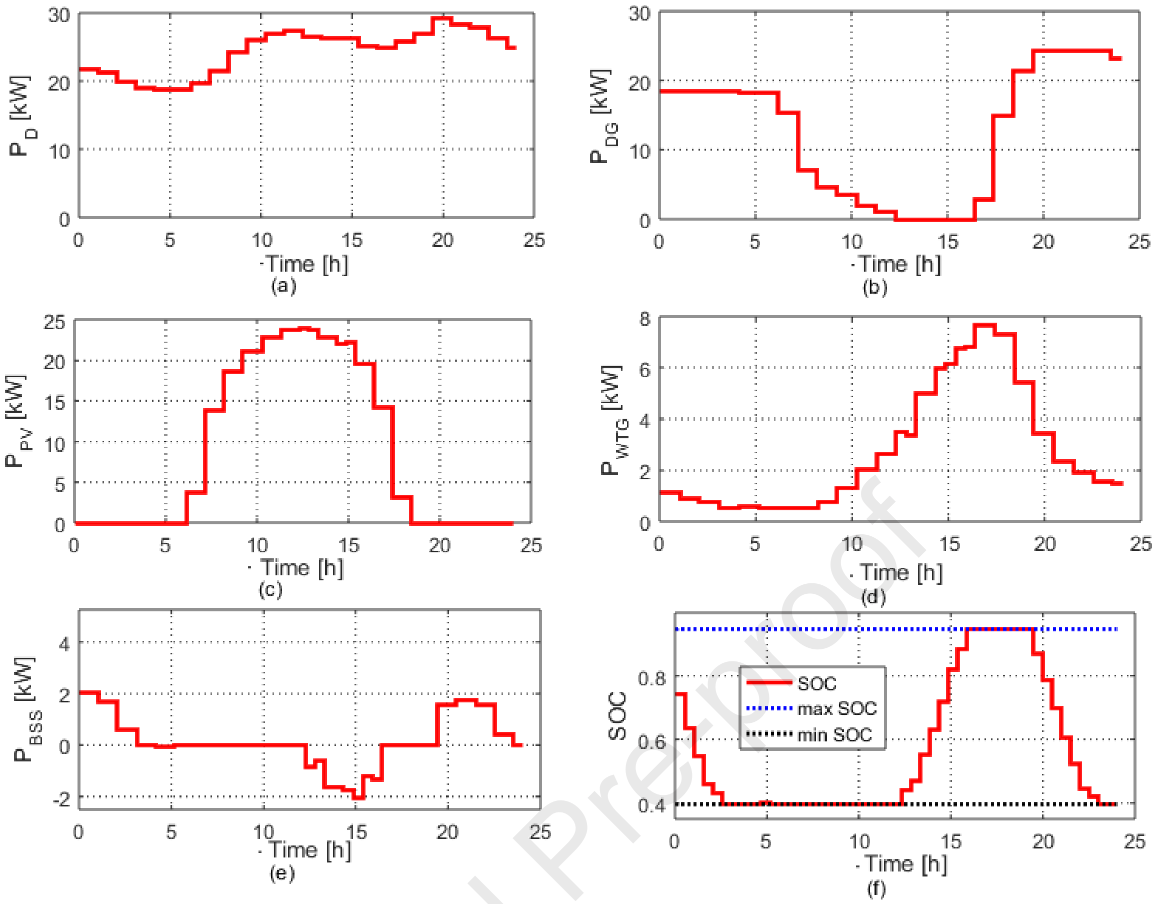

Fig. 16. Autumn weekend power flow and load profile: (a) Power demand, (b) DG power output, (c) PV power output, (d) WTG power output, (e) BSS power output and (f) SOC.

Scenario 5: Load Demand Pattern in the Winter Weekday

Owing to the dispatch strategy applied in this work, the power contribution of every component of a MGS and SOC is presented in Fig. 17 (a-f). The load flow pattern during the winter weekday is different from summer, owing to the seasonal changes and variation of load profile. Apart from this, WTG and PV significantly produce more power in the summer when compared with winter. The DG operates for a very long period in the winter when compared with summer, particularly early hours, and late hours of the day. Due to the sudden reduction in the values of wind and solar resources in winter, the DG is scheduled to work for 24 hours with different capacities as presented in Fig 17b. The DG is used as the main power source to balance the load demand in a situation where the combined operation of RERs and BSS cannot effectively respond to the load demand. The composition of the TC during the summer weekend by using DG and MGS is presented in Fig. 18a-b. The FC, MC, EC, TC, COE, CO_2, NOx and SO_2 by utilizing the MGS to satisfy the power requirements in winter weekday are $ 264.7098, $96.7051, $19.5534, $905.6875, 0.2728 $/kWh, 3.8136 kg, 0.2505 kg and 0.0781kg as presented in Fig.19 and Table 5. Hence, the TC, FC, MC, EC, COE, CO_2, NOx and SO_2 savings when compared with the DG only are $141.913, $233.222, $22.815, $ 10.7451 and $0.0427/kWh, 2.0957kg, 0.1377kg and 0.043kg as well as BCR of 1.648 as shown in Figures 8-10 and Table 4 with the application of RERs when compared with the circumstances where the DG is only utilised to meet the load demand. This demonstrates that 13.546%, 46.84%, 19.089%, 35.464% and 13.534% of TC, FC, MC, EC and COE savings are accomplished in this scenario as presented in Fig. 11. It is validated from the results presented in this case study that money spent on the above mentioned KPIs have been reduced considerably during the winter weekday when compared with only DG. The results presented in Table 5 show that the TC and COE in the winter weekday are 22.58% and 23.09% more than the TC and COE in the summer weekday when using the MGS. This shows that TC and COE savings in the summer weekday are 59.96% and 59.71% more than TC and COE obtained in the winter weekday.

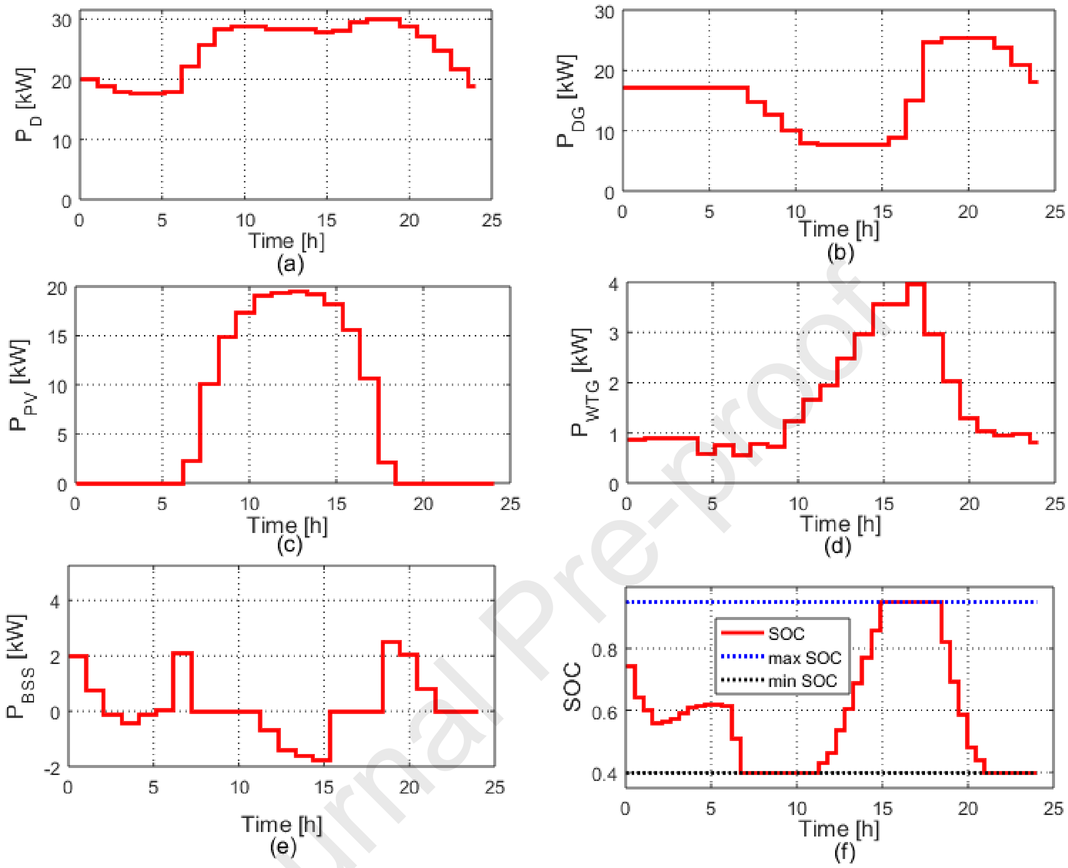

Fig. 17. Winter weekday power flow and load profile: (a) Power demand, (b) DG power output, (c) PV power output, (d) WTG power output, (e) BSS power output and (f) SOC.

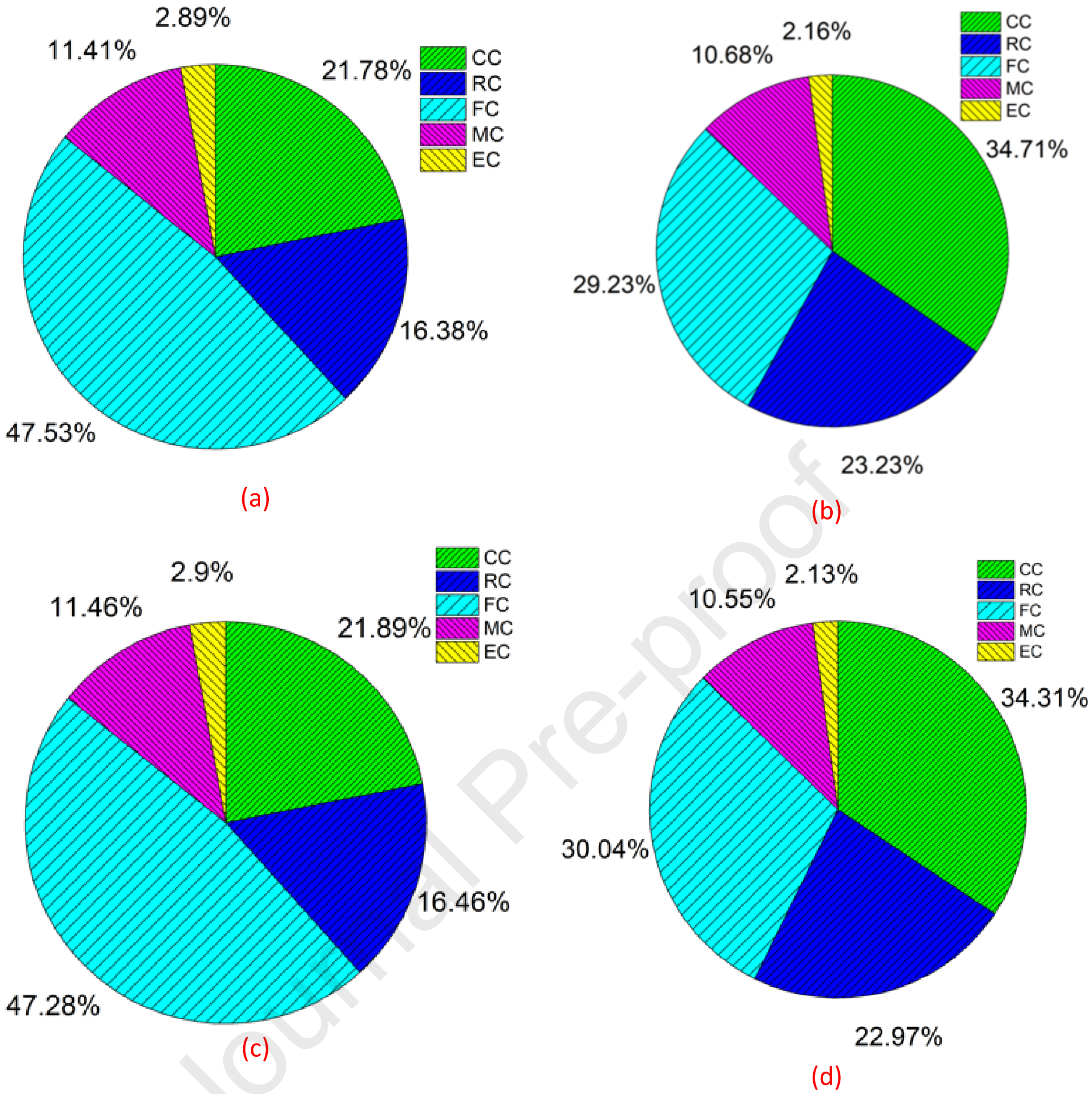

Fig. 18 Composition of total cost of the proposed power system: (a) Winter weekday DG only, (b) Winter weekday microgrid system, (c) Winter weekend DG only and (d) Winter weekend MGS.

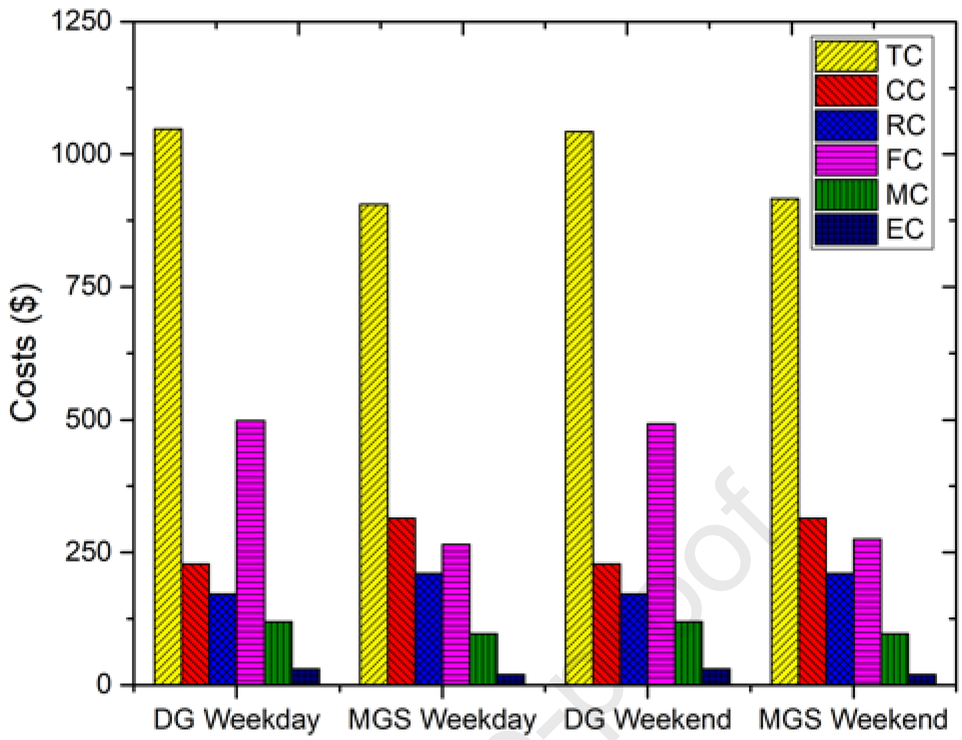

Fig. 19 Economic analysis of winter based on the seasonal variations

Table 5 Comparison of different seasons (winter and spring)

Seasonal variation	Winter				Spring			
	Weekday	Weekday	Weekend	Weekend	Weekday	Weekday	Weekend	Weekend
Description	DG only	Microgrid system	DG only	Microgrid system	DG only	Microgrid system	DG only	Microgrid system
CC ($)	228.2055	314.3356	228.2055	314.3356	228.2055	314.3356	228.2055	314.3356
RC ($)	171.6164	210.3836	171.6164	210.3836	171.6164	210.3836	171.6164	210.3836
FC ($)	497.9322	264.7098	492.9084	275.1767	497.0007	194.7192	496.7339	210.548
MC ($)	119.52	96.7051	119.46	96.6451	119.52	85.1916	120.12	86.1348
EC ($)	30.2985	19.5534	30.2833	19.5382	30.2985	14.5325	30.4506	14.831
TC ($)	1047.6	905.6875	1042.5	916.0792	1046.6	819.1625	1047.1	836.233
Total benefit ($)	-	141.913	-	126.420	-	227.438	-	210.867
COE ($/kWh)	0.3155	0.2728	0.3142	0.2761	0.3153	0.2467	0.3138	0.2506
CO_2 (g)	5.9093	3.8136	5.9063	3.8106	5.9093	2.8343	5.9389	2.8926
NOx (g)	0.3882	0.2505	0.388	0.2503	0.3882	0.1862	0.3901	0.19
SO_2 (g)	0.1211	0.0781	0.121	0.0781	0.1211	0.0581	0.1217	0.0593

Scenario 6: Load Demand Pattern in the Winter Weekend

The power generated by the DG, PV, WTG, BSS and load demand in the winter weekend is presented in Fig. 20 (a-e) and the corresponding SOC is presented in Fig. 20f. The composition of the TC during the summer weekend by using DG and MGS is presented in Fig. 18 (c-d). In this scenario, if the load demand is supplied from utilising the MGS, FC, MC, EC, TC, COE, CO_2, NOx and SO_2 in the winter weekend are $275.1767, $96.6451,

$19.5382, $916.0792, 0.2761$/kWh, 3.8106kg, 0.2503kg and 0.0781kg as presented in Fig. 19 and Table 5. The substantial discrepancy in TC and COE in winter weekday and weekend has been attributed to the load pattern of consumers. The FC is significantly high during the weekend because most of the people will be at home and be using different type of electronic gadgets. This demonstrates that the amount of money spent on diesel fuel consumption in winter weekend is 3.804% more than winter weekday by using the proposed MGS. When the proposed system is optimally operated with the combination of numerous power sources, the TC, FC, MC, EC, COE, CO_2, NOx and SO_2 savings and BCR are are $126.421, $217.222, $22.815, $10.7451, $0.0381/kWh, 2.0957kg, 0.1377kg and 0.0429kg and BCR of 1.468 as shown in Figures 8-10 and Table 4. This translates to 12.127%, 44.173%, 19.089%, 35.482% and 12.126% of the above mentioned KPIs when compared with the circumstances where the DG is only utilised to meet the load demand. It can be deduced from Table 5 that the TC and COE in the winter weekend are 1.13% and 1.195% more than winter weekday, while the TC and COE savings in the winter weekday are 10.92% and 10.77% winter weekend as presented in Table 4. This shows that a lot of money is saved in the winter weekday than a winter weekend owing to the load variations.

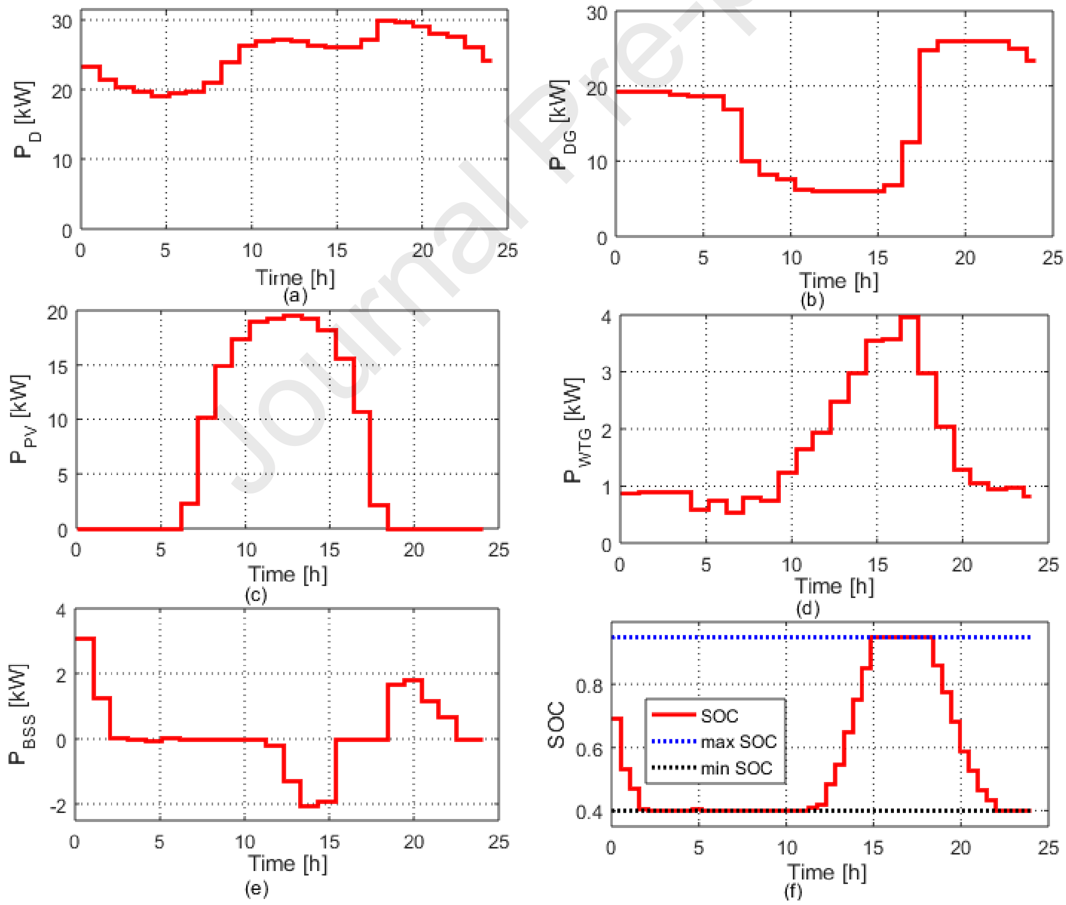

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Fig. 20. Winter weekend power flow and load profile: (a) Power demand, (b) DG power output, (c) PV power output, (d) WTG power output, (e) BSS power output and (f) SOC.

Scenario 7: Load Demand Pattern in the Spring Weekday

The load demand in the spring weekday and power produced by the components of the proposed MGS are presented in Fig. 21 (a-e) and corresponding SOC is shown in Fig. 21f.

The simulation results obtained in the spring weekday are quite different from the summer weekday based on seasonal variations of wind and solar resources and the difference in demand profiles. The availability of solar resources in the spring makes the PV system to be the major contributor of power to the load points. The composition of the TC during the spring weekend by using DG and MGS is presented in Fig. 22 (a-b). The FC, MC, EC, TC, COE, CO_2, NOx and SO_2 in the spring weekday with the utilisation of the PV, BSS and WTG are $ 194.7192, $85.1916, $14.5325, $819.1625 and 0.2467$/kWh, 2.8343kg, 0.1862kg and 0.0581kg as shown in Table 5 and Fig.23. The TC, FC, MC, EC, COE, CO_2, NOx and SO_2 savings of $227.438, $302.282, $34.3284, $15.766 and $0.0686/kWh, 3.075kg, 0.2020kg and 0.063kg and BCR of 2.641 have been shown in Figures 8-10 and Table 4 when the MGS is compared with only DG. This translates to 21.731%, 60.821%, 28.722%, 52.0356% and 21.757% of TC, FC, MC, EC and COE savings as presented in Fig. 11. Moreover, the values of TC and COE obtained in the winter weekday are 14.41% and 14.96% more than the summer weekday. This indicates that MGOs can earn TC and COE savings of 35.74% and 35.28% in the summer weekday more than the spring weekend. This shows that more cost savings are achieved in the summer weekday when compared with the spring weekday owing to the load variations and seasonal changes.

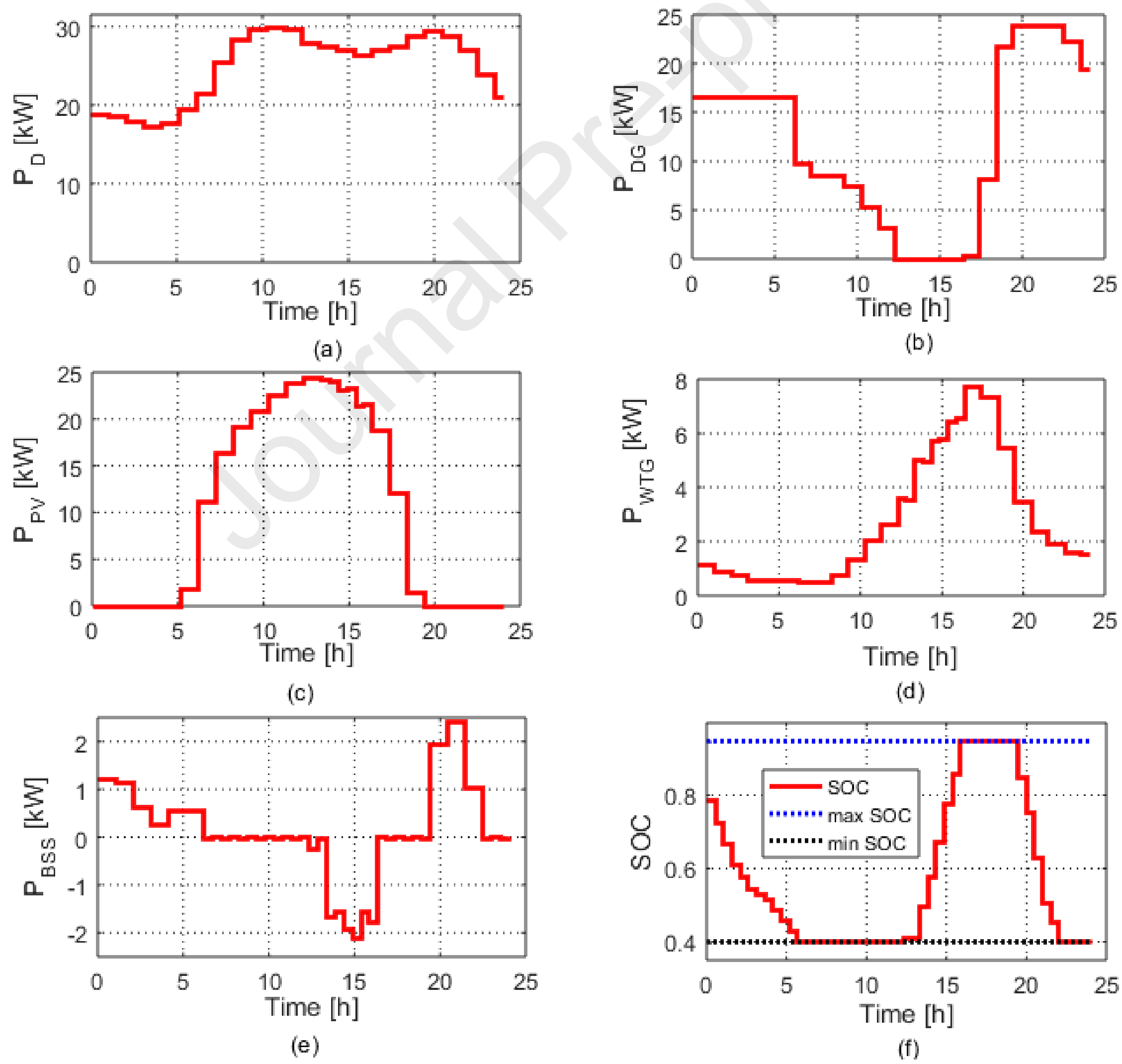

Fig. 21. Spring weekday power flow and load profile: (a) Power demand, (b) DG power output, (c) PV power output, (d) WTG power output, (e) BSS power output and (f) SOC.

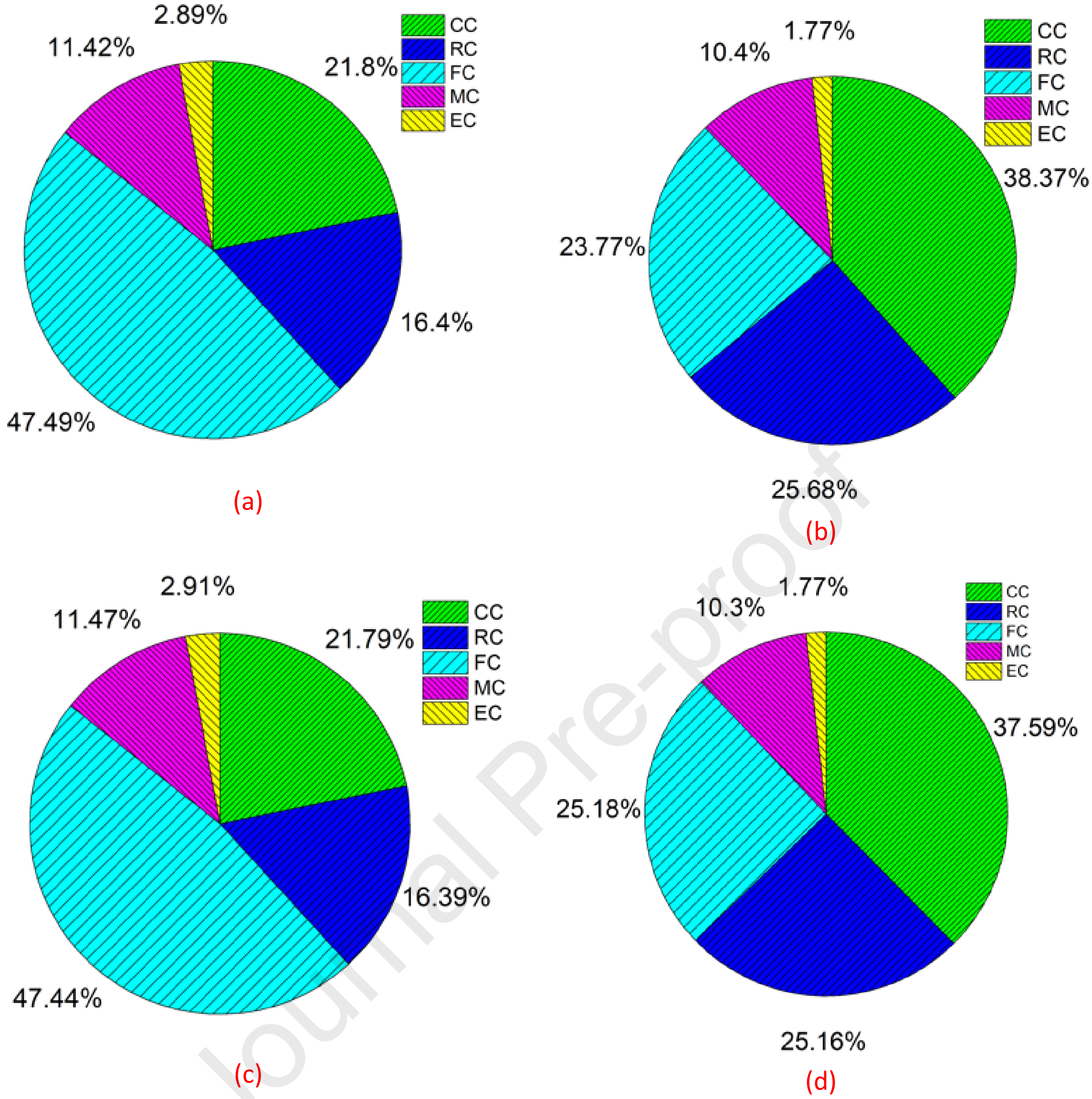

Fig. 22 Composition of total cost of the proposed power system: (a) Spring weekday DG only, (b) Spring weekday microgrid system, (c) Spring weekend DG only and (d) Spring weekend MGS

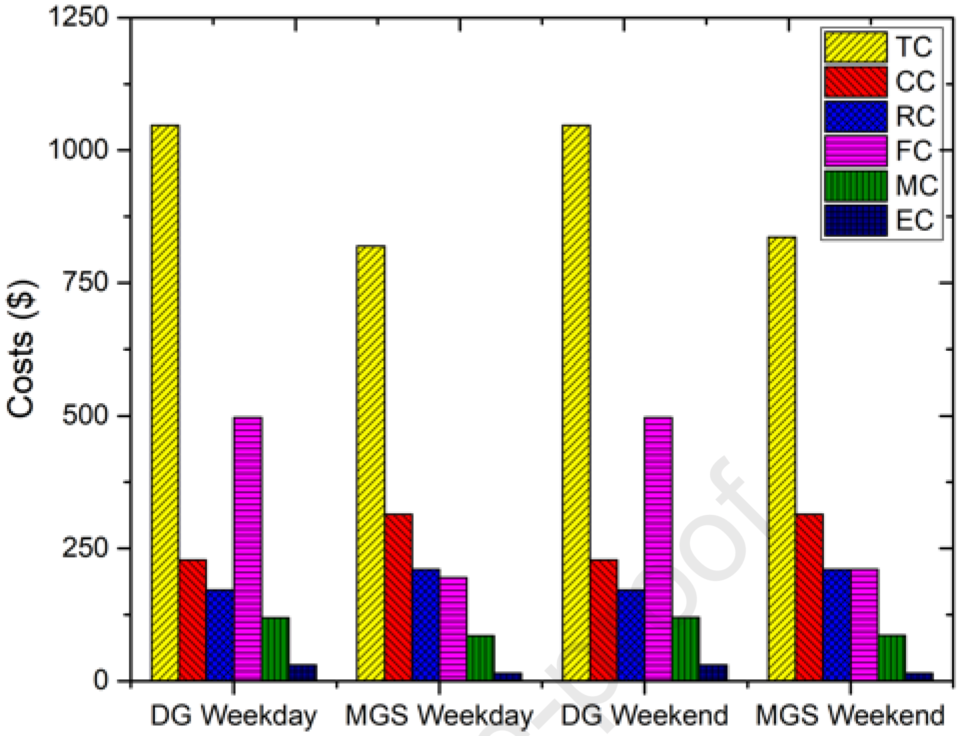

Fig. 23 Economic analysis of spring based on the seasonal variations

Scenario 8: Load Demand Pattern in the Spring Weekend

In this scenario, a MGS is structured to satisfy the load demand of low electrical consumption applications in the spring weekend. The load demand in the spring weekend is presented in Fig. 24a. The power generated by components of the proposed MGS and the corresponding SOC of the BSS is presented in Fig. 24 (b-f). The composition of the TC during the spring weekend by using DG and MGS is shown in Fig. 22 (c-d). The FC, MC, EC, TC, COE, CO_2, NOx and SO_2 obtained in this scenario with the application of MGS are \$210.548, \$86.1348, \$14.831, \$836.233, 0.2506 \$/kWh, 2,8926kg, 0.19kg and 0.0593kg shown in Table 5 and Fig. 23. The TC, FC, MC, EC, COE, CO_2, NOx and SO_2 savings of \$210.867, \$286.186, \$33.9852, \$15.6196 and \$0.0632/kWh, 3.075kg, 0.2001kg and 0.0624kg and BCR of 2.448 are attained with the application of RETs as shown in Figures 8-10 and Table 4. This translates to about 20.138%, 57.61%, 28.29%, 51.29% and 20.14% of TC, FC, MC, EC and COE savings as presented in Fig. 11 when compared with the circumstances where the DG is used alone to meet the load demand. The simulation results obtained in the spring weekend are different from the spring weekday based on the difference in demand profiles. It is well established from the results obtained in this scenario that the TC and COE with the hybridisation of RERs in the spring weekend are 2.04% and 1.56% more than the one obtained in the spring weekday owing to the variations in the load demand. This shows that TC and COE savings obtained in the spring weekday are 7.29% and 7.87% more than the values obtained in the spring weekend owing to the load variations and seasonal changes. The results obtained in the study show that GETs can be globally used to reduce the values of TC and COE significantly.

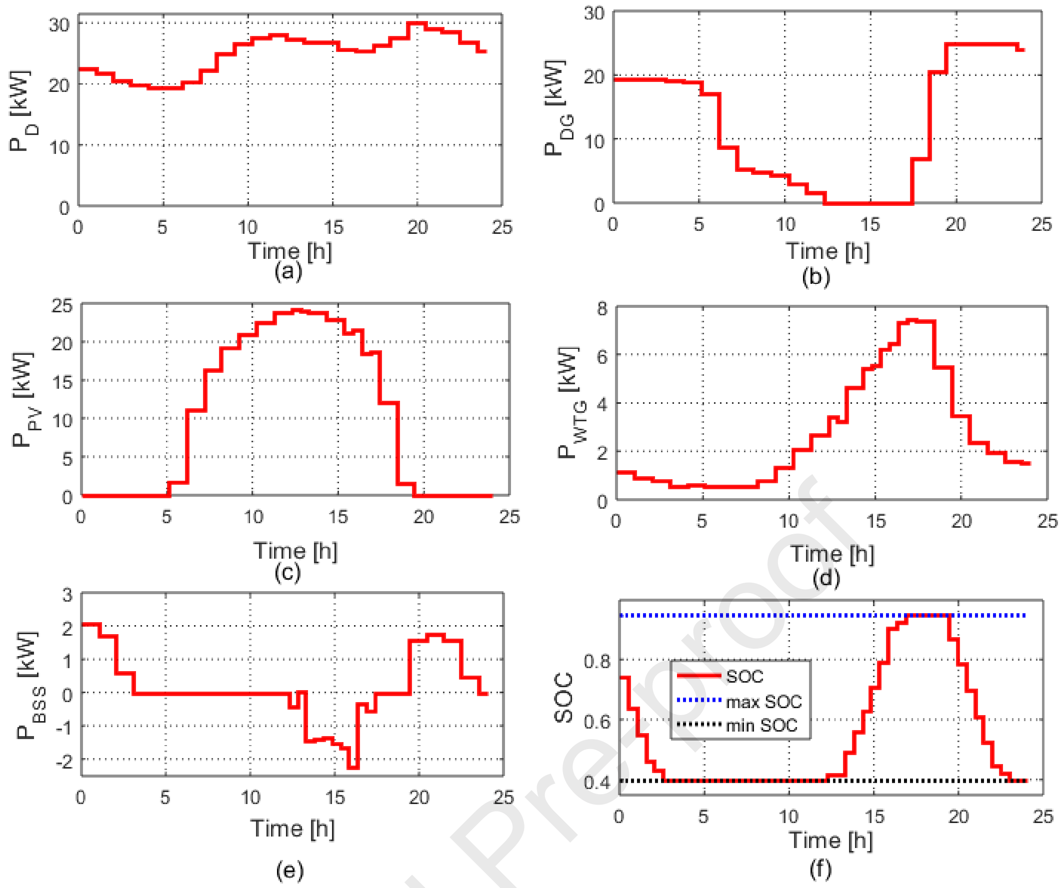

Fig. 24. Spring weekend power flow and load profile: (a) Power demand, (b) DG power output, (c) PV power output, (d) WTG power output, (e) BSS power output and (f) SOC.

6. Sensitivity analysis

The impacts of varying the input parameters and effects of uncertainty of some resources on the optimal operation of the power systems can be assessed by using the methodology applied in the study. The sensitivity analysis permits the MGOs to forecast the characteristics of their power systems when operating with numerous conditions. The renewable energy strategy in summer weekday (MGS) offers the best results when compared with other seasons. In view of this, the sensitivity analysis is carried out by using the operating parameters of summer weekday.

6.1. Effects of varying the diesel fuel cost

The fluctuations in the cost of diesel fuel are one of the major factors that affect the economic performance of a MGS. The diesel fuel cost was varied from 60% to 140% of its actual cost as presented in Table 2 and its impacts on the TC and COE were evaluated as shown in Fig. 25. The TC and COE increase as the diesel fuel cost increases. The results of the sensitivity analysis show that TC and COE increase with an increase in the diesel fuel cost. For this reason, the best option is to integrate the GETs into the existing traditional power system. This will reduce the economic impacts that are associated with the fluctuation of diesel fuel cost.

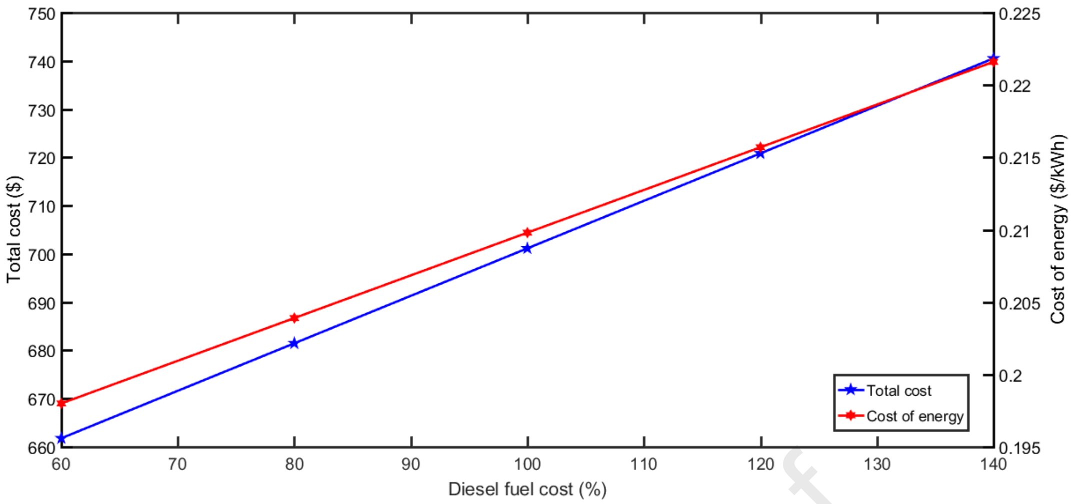

Fig. 25. Effect of diesel fuel cost on TC and COE

6.2. Effects of varying the capital cost

The e□ects of varying the capital cost of the proposed MGS is investigated in the study. The capital costs of DG, PV, WTG and BSS are varied from 60% to 140% of their capital costs. Fig. 26 (a-f) show that TC and COE change in proportion with the capital cost of the above mentioned components. The variations in the capital cost have a substantial e□ect on the operation of the proposed power system. For this reason, certain policies such as tax relief, technology innovation, rebates, incentives and renewable energy initiative must be promoted to reduce the costs of renewable energy components.

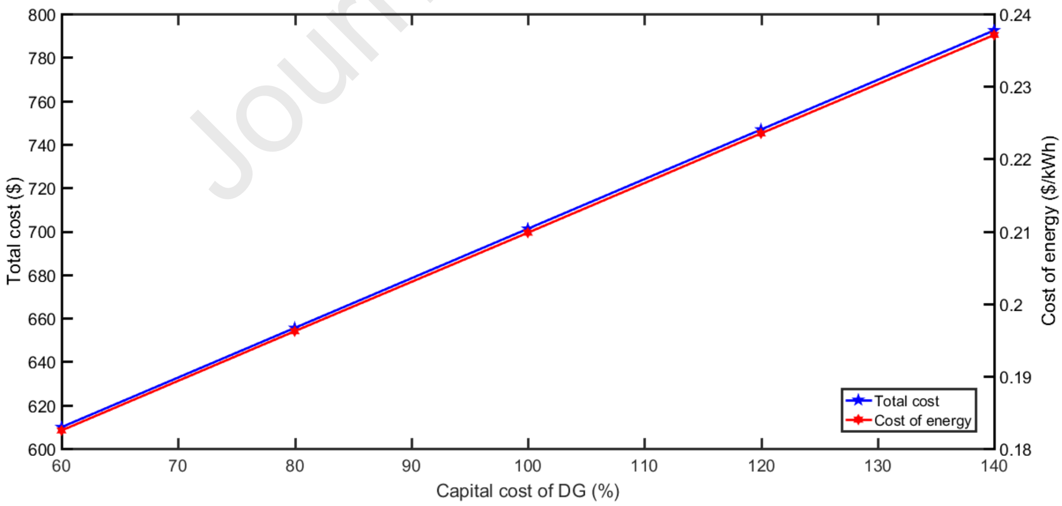

Fig. 26a. Effect of capital cost of diesel generator on TC and COE

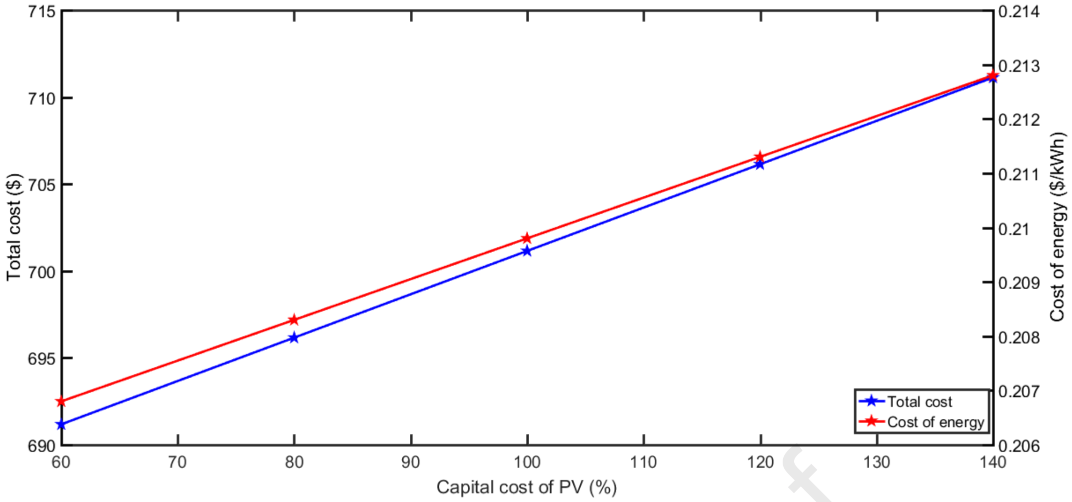

Fig. 26b. Effect of capital cost of PV on TC and COE

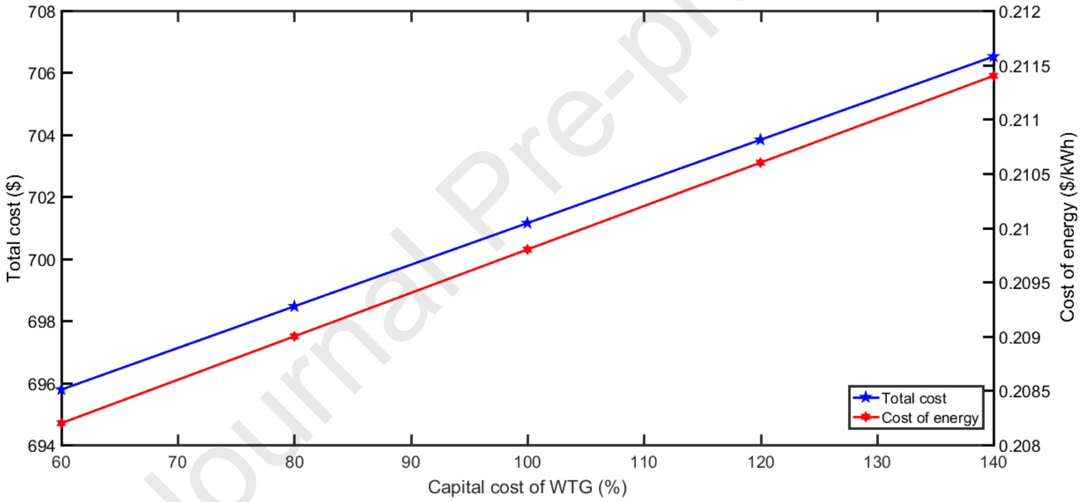

Fig. 26c. Effect of capital cost of WTG on TC and COE

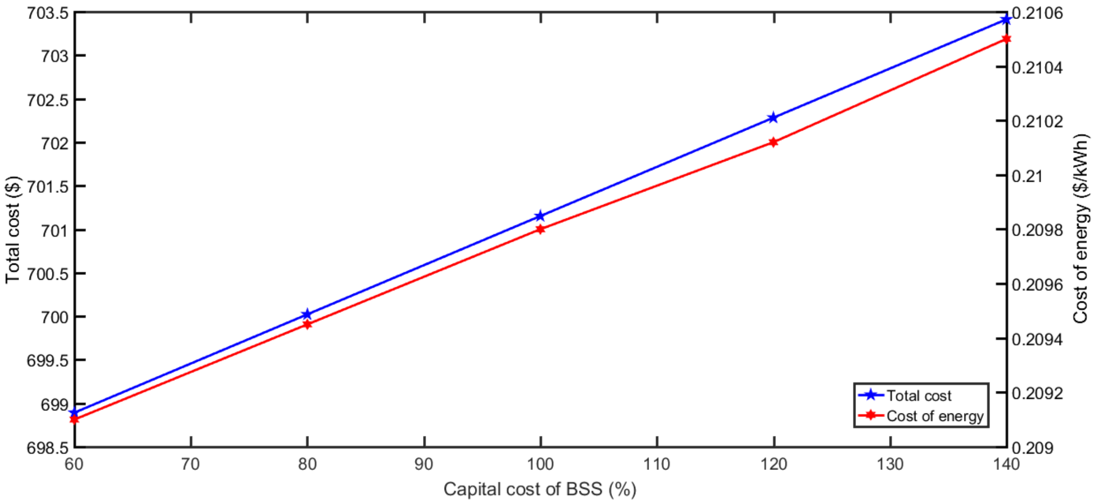

Fig. 26d. Effect of capital cost of BSS on TC and COE

6.3. Variation of maintenance cost

The maintenance cost of each component of the proposed power system is varied from 60% to 140% of the actual cost maintenance. Fig. 27 (a-f) show that TC and COE increase with an increase in the maintenance cost of the system. This shows that the maintenance cost has a direct proportion on the TC and COE of the power system.

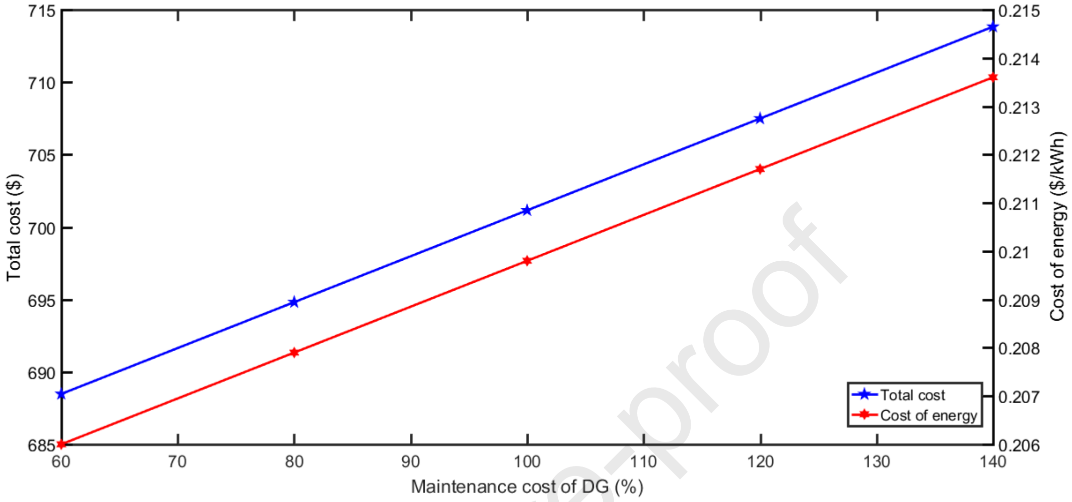

Fig. 27a. Effect of maintenance cost of DG on TC and COE

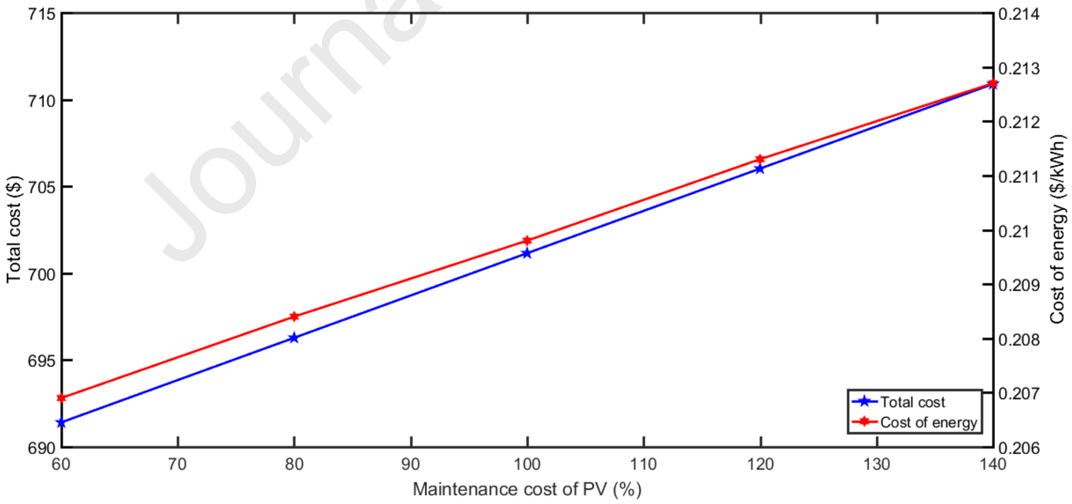

Fig. 27b. Effect of maintenance cost of PV on TC and COE

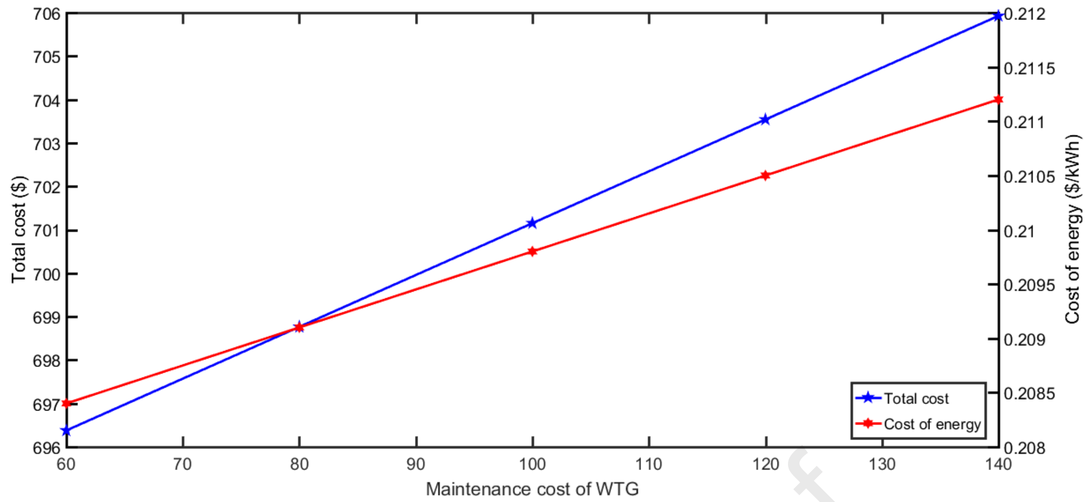

Fig. 27c. Effect of maintenance cost of WTG on TC and COE

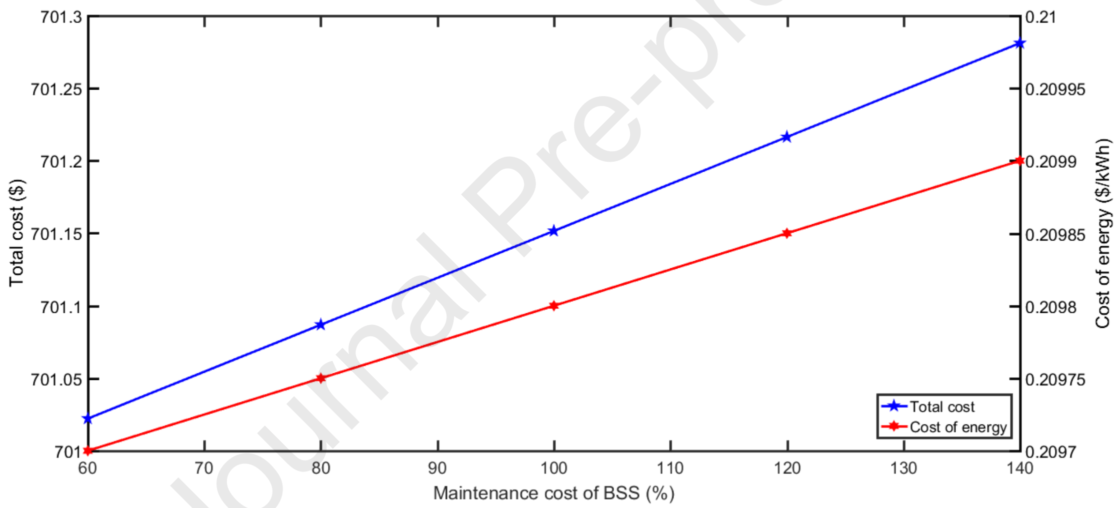

Fig. 27d. Effect of maintenance cost of BSS on TC and COE

6. Conclusions

The access to a stable power supply is a prerequisite for the development of any country; therefore, it will improve the standard of living and have positive impacts on the commercial and industrial activities. This research work proposed a power control strategy to minimise the TC and COE and operation of the DG and BSS while maximising the utilisation of PV and WTG in off-grid power system. The optimisation model proposed in this work results in cost savings when compared with a scenario where DG alone is used to satisfy the power requirement. Therefore, it is clearly deduced from the outcomes of the research work that FC, MC and EC are minimised and the usage of RETs is maximised. The results show that the power demand is effectively shared among the components of a MGS based on the operating limits. The approach applied in this paper can be used by the decision makers of numerous utilities to solve multi-objective functions of a MGS that operate with the various generating units. The energy management model applied in this work can be used in residential and commercial buildings for power solution applications and to serve as a practical strategy for the development of the integrated power system. The GETs can be used by the MGOs to increase the capacity of the global power generation and reduce the subsidies on the importation of crude oil. The global energy security can be improved with the introduction of the strategies that encourage massive utilisation of the GETs in the traditional power system.

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Highlights

- The fuel cost benefits of utilizing renewable energy resources are presented.
- This research can promote and strengthen energy security.
- This work can improve access to the power supply in the rural areas.
- The proposed technique can be used for the cost savings and sustainability of energy.
- This work can be used as benchmarks for renewable energy sustainability projects.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: