Bi-objective economic feasibility of hybrid micro-grid systems with multiple fuel options for islanded areas in Egypt

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**Abstract**

The main target of this research is to allow modern distributed energy resources (DERs) to contribute effectively in the economic feasibility of hybrid renewable power generation system. There are several factors such as the net present cost (NPC), levelized cost of energy (COE), amount of greenhouse gases (GHG) emissions, and the ability of the hybrid system to meet the load at different meteorological conditions to consider when evaluating the effectiveness of hybrid generation system within microgrids. A multi-objective based optimization algorithm to reduce cost, emissions, and a combined solution between cost and emissions is investigated in this research. This research presents an approach to optimize a hybrid microgrid (HMG) system with different fuel options. The power management approach determines the optimal sizing of DERs based on ant colony optimization (ACO) algorithm. In order to find the best configuration, the obtained results are compared with genetic algorithm (GA), particle swarm optimization (PSO), and HOMER. Three isolated areas in Egypt with different meteorological conditions are selected for optimization of HMG system, namely: Kharga, Saint Katherine, and Qussair. The results show that the combined optimal configuration of HMG system is better in satisfying load demands without violating any restraints.

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1. Introduction

Recently, generated electricity from renewable energy resources has become attractive for designers and system engineers due to recent development environmental issues, increase in power consumption and prices, and expected future depletion of fossil fuel [1,2]. In many countries, several rural villages are still remote from conventional power grid [3,4]. However, every area has a strong potential to utilize its ample, free, and renewable energy resources such as photovoltaic (PV) and wind energy combined with modern distributed energy resources (DERs). Thus, much rural economy development could be integrated by utilizing optimal HMG system.

In the literature, hybrid wind/solar energy supplies are common and traditional renewable energy resources in remote areas [3,5]. However, intermitted nature of generated power may create variations of the output voltage, frequency, and power [6]. Additionally, during failure or inaccessibility for one or more of the operating generators, MG will not be able to meet its load demand. Thus, energy storages and diesel generators can be placed in HMG system. However, generally the utilization of diesel as fuel option increases the overall cost [7].

Hybrid microgrid (HMG) systems enable the utilization of DERs combined with conventional resources. Current studies offer a considerable development in design and analysis of such systems over the past decade [8]. In Ref. [9], it was found that the combination between PV and wind energies reduced green-house gas emissions (GHG) and diesel consumption by 50%. The authors of [10] assessed the economic and environmental aspects of a standalone renewable-based power generation system for electrification of rural areas for five hybridization cases in Yemen. The results of optimization based on cost of energy (COE) using HOMER model found that hybridization of PV and wind power generation system succeeded in reduction of 100% and 30% in the GHG emission. In Ref. [11], a study on the economic feasibility based on COE using HOMER was conducted for a special off-grid town in China. The authors showed that renewable power hybridization could mitigate GHG emissions by 40–70% compared to electricity from conventional resources or existing utility grid. The authors of [11] concluded that coal based power stations was not a proper choice for COE and GHG perspectives. In Ref. [12], the authors detailed the
different renewable energy resources in Algeria. They claimed that PV/wind/diesel was the most appropriate configuration for the investigated areas. N. M. Isa in Ref. [13] developed a cogeneration system of PV/Fuel cell/Battery using HOMER for hospital building in Malaysia. The results indicated that the proposed cogeneration system had the lowest total net present cost (TNPC) and COE. The work conducted in Refs. [3–13] focused on minimizing TNPC, COE, or loss of power supply probability (LSPS). Even though they referred to GHG emissions reduction, they did not consider GHG emissions on the objective function.

For electric power deficient rural locations, utilization of the available energy resources for electrification is attractive options. Biomass generators were combined with multiple renewable resources in Refs. [14,15]. The work conducted in Refs. [14,15] showed that biomass generators are futuristic and viable option for rural areas.

Not much work in the literature has discussed the hybridization of biomass with PVs and wind energies. The authors of [16] proposed a hybrid HMG system comprising PV/Wind/biomass for rural areas in India via HOMER software. In Ref. [2], a hybridization system comprising PV/biomass/wind/battery to electrify an islanded microgrid via artificial bee colony algorithm was developed. In Ref. [17] a PV/biomass/wind system was investigated for rural areas in Bangladesh via HOMER. Similar work was conducted in Ref. [18]. In Mozambique, the techno economic analysis to electrify off-grid areas was conducted in Ref. [19]. It was concluded that food and agricultural wastes could be used to electrify rural areas.

In Ref. [20], an economic emission dispatch with considering the stochastic nature was considered. However, only wind turbine analysis was conducted. The wind and solar power using optimal power flow with load uncertainty was discussed [21]. In Ref. [22], optimal day ahead scheduling problem with considering power to gas conversion probability was conducted. However, only total costs objective function was considered regardless the impact of emissions. In Ref. [23], a multi objective economic environmental power dispatch study with stochastic wind-solar-small hydro power was conducted.

The investigation of the above work reveals that most studies involve single objective (fitness) function related to system costs. This may result in negative impacts upon other objectives. In Refs. [20–23], the available environmental multiple fuel options were not addressed. Some works [3,24] utilize weighting factors for solving multi-objective problems. However, this may lead to misleading conclusion. This encourages the authors to develop a bi-objective fitness function to compromise between GHG and COE.

There are several configuration of hybrid microgrid (HMG) systems can be utilized to feed the electricity for isolated areas. In each country, the choice of the suitable HMG system varies according to weather condition, availability of renewable energy resources, and economical and environmental aspects. The motivation of this study is that there are around 167000 citizens in Egypt according to New and Renewable Energy Authority (NREA) are suffering from lack or completely deprived from electricity [25]. Such households are distributed around 264 isolated villages in nine towns along Egypt. Among these villages, 211 villages are completely isolated from electricity and the remaining are fed through standalone diesel stations. This study concerns in electrifying the fully isolated areas by optimizing HMG system, which can meet the load in these areas with respect to minimal TNPC, COE, and CO2 emissions. Most of these isolated villages are located in desert areas, where abundant amount of solar energy and in some places wind energy exists also. A hybrid PV/wind power generation system is typically renewable HMG system. However, this system may face failures to meet the load demands because of battery shortage at lack of solar and wind energy due to change in weather conditions. Diesel generator can be used as backup for this system to cover the lack in electricity.

At present, most studies focus on utilizing software packages [2], HOMER is widely used for solving HMG system configuration design [26,27]. However, software packages have disadvantages such as black box data entry utilization and single objective minimization. Conventional techniques such as iterative method [24], graphical construction method [28], and linear programing [29] have been utilized to solve HMG system configuration problem. However, conventional techniques are often trapped with local minima [2]. Meta-heuristic techniques can effectively be used to solve a number of complicated engineering problems. Genetic algorithm (GA) is employed in Refs. [30,31] to find the best HMG system configuration. Particle swarm optimization (PSO) is employed to find the best HMG system configuration [32]. Bee colony (BC) [21,22], harmony search algorithm (HA) [32], Biography algorithms are used in Ref. [33] for various HMG systems. To the best of authors knowledge, limited work are found, where the hybridization of PV–wind–biomass–fuel cell (FC) and microturbine based on natural gas (NG) combined with energy storage have been investigated.

In light of the above literature review, there is a need for hybridization of PV–wind–biomass–FC and NG based micro turbine combined with energy storages. In addition, each dispatchable DG has its own price and carbon footprints, which contributes positively in the global optimization. Determining the best configuration and sizing of each dispatchable and renewable DERs is a challenging task. Despite of the work in literature, optimal sizing of hybrid systems has been identified by either software tool or evolutionary techniques. However, none of above studies dealt with optimal sizing of PV–wind–biomass–FC and NG based micro turbine combined with storage battery using bi-objective evolutionary algorithms. The main contribution of this work is to design

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**Acronyms**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ACA</td>
<td>Ant colony algorithm</td>
</tr>
<tr>
<td>AD</td>
<td>Autonomy days</td>
</tr>
<tr>
<td>BOACA</td>
<td>Bi-objective ant colony algorithm</td>
</tr>
<tr>
<td>COE</td>
<td>Cost of energy ($/kWh)</td>
</tr>
<tr>
<td>CUF</td>
<td>Capacity utilization factor</td>
</tr>
<tr>
<td>DERs</td>
<td>Distributed energy resources</td>
</tr>
<tr>
<td>DG</td>
<td>Dispatchable generator</td>
</tr>
<tr>
<td>DOD</td>
<td>Depth of discharge (%)</td>
</tr>
<tr>
<td>FC</td>
<td>Fuel cell</td>
</tr>
<tr>
<td>GHG</td>
<td>Green-house gas</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic algorithm</td>
</tr>
<tr>
<td>PSO</td>
<td>Particle swarm optimization</td>
</tr>
<tr>
<td>HMG</td>
<td>Hybrid Microgrid</td>
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<tr>
<td>LCA</td>
<td>Life cycle assessment</td>
</tr>
<tr>
<td>LSPS</td>
<td>Loss of power supply probability</td>
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<tr>
<td>MH</td>
<td>Microgrid</td>
</tr>
<tr>
<td>NG</td>
<td>Natural gas</td>
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<tr>
<td>NGT</td>
<td>Natural gas turbine</td>
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<tr>
<td>NOCT</td>
<td>Normal operating cell temperature (°C)</td>
</tr>
<tr>
<td>NPC</td>
<td>Net present cost</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic cell</td>
</tr>
<tr>
<td>TNPC</td>
<td>Total net present cost</td>
</tr>
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</table>
a robust bi-objective algorithm in order to allow the investigated HMG system renewable and dispatchable resources to participate effectively in satisfying load demands without violating any restraints. For this purpose, three different areas with different meteorological conditions are adopted to test the capability of the developed algorithm to minimize cost and CO₂ emissions due to the penetration of the renewable and dispatchable resources. In addition, several operating conditions scenarios are discussed. For this purpose, a modern meta-heuristic algorithm is developed. The results of developed algorithm are compared with mature algorithms such as genetic and PSO algorithms.

The ant colony bi-objective algorithm (ACA) has been used to realize the best configuration of the developed system to fulfill the electrification demands of a small isolated village in Egypt’s deserts. The motivation to use this solution is that compromised solutions are not provided by software packages such as HOMER. The major factor that differentiate ACA from other evolutionary algorithms is that ACA is consequential algorithm. ACA algorithm ends when all ants travel through the same path [34]. It is used to solve many engineering problems with appropriate convergence [35–37]. To prove the effectiveness of the developed technique, the obtained results are compared with GA, PSO, and HOMER.

To propose an economic generation of an HMG system with multiple options, the main goals of this study are outlined as follows.

- To develop a bi-objective model comprising between COE and GHG emissions. In addition, a mathematical model of the autonomous components is developed in this study.
- To develop the optimal size and configuration of the individual DERs with least COE, GHG emissions, and the combined solution.
- To discover the performance of the HMG system in critical situation such as failure or interruption of any renewable or DER units.

The reminder of this study is organized as follows. The description of the investigated areas is given in section 2. Problem description along with mathematical modeling of each component is presented in section 3. Problem formulation along with constraints is given section 4. Results and discussions are given in section 5. Finally, the concluding remarks are introduced in section 6.

### 2. Case study

This research concerns about optimizing an HMG system configuration which can meet the load with respect to minimal net present cost (NPC), cost of energy (COE), and CO₂ emissions at three isolate areas. The first area is Saint Catherine, located at northeastern of Egypt. It is geographically located at latitude of 28 north and longitude of 34 east. Kharga is the second selected area, which is located in central region in Egypt at latitude 25 north and longitude of 30 east. Quseer is the third area, which lies in southeastern of Egypt. It is located in geographical coordinate of 26 north and 34 east. Table 1 illustrates the summary of the average solar radiation and wind speed of the selected areas. According to the availability of local energy resources, as will be illustrated in the next section, Fig. 1 shows a hybrid standalone microgrid system where AC load, diesel generator, biomass gasifier and natural gas turbine are connected directly to AC bus. Moreover, solar PV modules, wind turbines, natural gas fuel cell and batteries are connected to the AC bus via DC/AC converter. The system given in Fig. 1 will be investigated in the following sections in order to determine the optimal sizing of each power generator according to the investigated objective functions. The developed HMG system is most appropriate for off-grid agricultural based or rural areas in developed counties.

### 3. Problem description

#### 3.1. Modeling of hybrid micro-grid system components

This study focuses on the formulation of new HMG system to electrify off-grid locations. The considered types of DERs include natural gas turbine, natural gas fuel cell, battery bank, diesel generator, and biomass generator. The renewable energy resources include PV and wind turbine generator. The modeling of selected components is presented in the following sub-sections.

##### 3.1.1. PV module

The solar atlas indicates that Egypt, as one of the sun-belt countries, is endowed with high intensity direct solar radiation of 2000–3200 kWh/m²/year from north to south. Sunshine duration throughout the year ranges from 9 to 11 h with few cloudy days. Solar energy ensures high potential for power generation reaching an economic potential of about 74,000 TWh/year. The output power delivered from each module at time t is depending on available solar radiation (S) and surface temperature (Teq) is calculated from the following equations. From the literature, the key findings is to find optimal power of the PV module to minimize the total costs [2,3,38,39].

\[
P_{PV(t)} = P_{PV,ref} \times \frac{S(t)}{S_{ref}} \times \left[1 + \beta_{ref}(T_e(t) - T_{ref})\right]
\]

Where

\[
T_e(t) = T_0(t) + \frac{NOCT - 20}{800} \times S
\]

where, \(T_0\) is the ambient temperature (°C) of the site under consideration at hour t and NOCT is the normal operating cell temperature. NOCT is defined as the cell temperature when the PV module operates under 1000 W/m² of solar irradiation and 20 °C of ambient temperature. It is usually between 42 °C and 46 °C.

The hourly solar radiation during one year as obtained from NASA historical data for the selected three areas are shown in Fig. 2 [40].

##### 3.1.2. Wind turbine generator

Power extracted from the wind (\(P_w\)) can be calculated as given in Eq. (3).

<table>
<thead>
<tr>
<th>Area name</th>
<th>Average solar radiation (kWh/m²/d)</th>
<th>Average wind speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saint Catherine</td>
<td>6.07</td>
<td>4.61</td>
</tr>
<tr>
<td>Kharga</td>
<td>6.24</td>
<td>5.69</td>
</tr>
<tr>
<td>Quseer</td>
<td>6.63</td>
<td>5.39</td>
</tr>
</tbody>
</table>
The mechanical power generated by the turbine follows Eq. (4).

\[ P_{WT}(t) = \begin{cases} 
P_t \left( \frac{V^3(t) - V_{ci}^3}{V_{r}^3 - V_{ci}^3} \right), & V_{ci} \leq V \leq V_r \\
V_r \leq V \leq V_{co} \\
0 & V_{co} \leq V \text{ or } V \leq V_{ci}
\end{cases} \]  

(4)

Where, \( P_t \) is the rated power, \( V_{ci} \) and \( V_{co} \) are cut in and cut out speed of the wind turbine, respectively. Actually, the speed of wind changes with height. Therefore, wind speed at desired hub height of wind turbine \( V_{WT} \) at certain location can be calculated from following equation with respect to reference wind speed \( V_{ref} \).

\[ V_{WT}(t) = V_{ref}(t) \left( \frac{h_{WT}}{h_{ref}} \right)^\alpha \]  

(6)

where, \( h_{WT} \) is the height of wind turbine hub, \( h_{ref} \) is the height of reference point where an anemometer is installed, and \( \alpha \) is the friction coefficient. The friction coefficient is a function of wind speed, temperature, height above ground, roughness of terrain, and time of the year. The common value of \( \alpha \) is 1/7 [2,3,39,41]. For wind energy, the key finding is clarified by finding the optimal wind energy based on the available wind energy from the istorical data.

### 3.1.3. Diesel generator

In hybrid standalone system, diesel generator is considered as back-up source to supply load in case of shortage of the other sources or depletion of the battery during peak load demand. The rated output power of the diesel generator unit used in this study is 4 kW. The initial capital and replacement costs are assumed to be $1000 per kW of diesel generator. The O&M cost of the diesel generator is 0.39$/kWh. The diesel generator has the lifetime of 24,000 h. Diesel fuel consumption \( Con_{dis} \) in L/h depends on output power and can be calculated from:

\[ Con_{dis}(t) = B_g + P_{dis}(t) \]  

(7)

where, \( P_{dis} \) is the rated power, \( P_{dis}(t) \) is the output power of the diesel generator at time \( t \), and \( B_g \), \( A_g \) are the coefficients of the consumption curve, equals 0.0845 L/kW and 0.246 L/kW, respectively [3]. The hourly cost of diesel fuel consumption can be determined from Eq. (8).

\[ C'_{dis} = Con_{dis}(t) \cdot f_{dis} \]  

(8)

where, \( f_{dis} \) is diesel fuel price in $/L. The role of diesel generator in economic feasibility studies is to supply the load demands in case of deficient energy supply from renewables and battery [3,13,42].

#### 3.1.4. Battery model

Batteries are the most vulnerable part of a standalone system. Choosing batteries for any standalone system depends on the following four factors: cost, application, maintenance, and life expectancy. They store energy and are usually specified as voltage and capacity in Amp-hours. The required storage capacity of the battery system in kWh can be calculated using Eq. (9) [2,13,28,39,42].

\[ E_{Batt} = \frac{E_l + AD}{\eta_{Batt}*\eta_{inv}} \]  

(9)

where, \( E_l \) is the average load demand, \( AD \) the battery autonomous days (i.e. the maximum number of days the battery can supply continuous energy without a recharge by any power source), approximately 3–5 days, DOD is maximum permissible depth of discharge of the battery, \( \eta_{Batt} \) and \( \eta_{inv} \) are the battery and inverter efficiencies. Typical values for DOD, \( \eta_{Batt} \), and \( \eta_{inv} \) are 80%, 85%, and 95% respectively [3].

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![Schematic of hybrid micro-grid system.](image)
3.1.5. Modeling of biomass gasifier generator

Biomass gasification process is converting the solid bio-residues into gaseous fuel, which is used to produce electrical energy. N. Said et al. presented the evaluation of biomass quantity and potential of biomass resources as fuel source in Egypt [43]. The obtained outcomes indicated that Egypt produces significant quantity of biomass with theoretical energy content of $416.9 \times 10^{15}$ J. There are several resources of biomass fuel in Egypt such as agriculture residues (maize residue, wheat straw, rice straw, and sugar cane residue ... etc.) and animal wastes, human being wastes and sewage sludge. Agricultural residues, which comes from crop is being considered as the leading sources of biomass wastes in Egypt, then human being food wastes and finally, the animal and sewage wastes. The quantity of biomass produced from rice straw is 63.75% of total biomass production from agricultural crop offal, which around 12.33 million tons/year [43]. The annual electricity power generated from the biomass gasifier generator ($E_{Bio}$) can be estimated from the following equation:

$$E_{Bio} = P_{bio} \times 8640 \times CUF$$  \hspace{1cm} (10)

Where $P_{bio}$ is the rating of biomass gasifier generator and $CUF$ is the capacity utilization factor [2,6,14,16,39].

3.1.6. Modeling of natural gas turbine (NGT)

One of promising fuel options in Egypt is natural gas fuel because of its widespread infrastructure. Burning natural gas produces lower greenhouse gas emissions than the other conventional fossil fuels such as oil and coal. Thus, natural gas is more environmental friendly than oil and coal. Currently, production of natural gas in Egypt is assessed at around 4.4 billion cubic feet per day (BCF/d), and is projected to grow by 1.5 BCF/d by the end of 2017 according to a February statement by the Egyptian petroleum ministry. Fig. 3 shows the gradually growth of total annual production of natural gas in Egypt during the period from 1990 to 2017 [44]. Moreover British Petroleum (BP) Company, which produces around 40% of Egypt’s total gas, has been targeting to rise investments in Egypt, with strategies to invest about $13 billion before 2020, according to a November 2016 press released by the UK embassy in Cairo [45].

The model equations of natural gas turbine which includes the fuel consumption of natural gas unit ($Q_{NGT}$) and total greenhouse gas emissions ($GHG_{NGT}$) are indicated as in Eqs. (11) and (12)
respectively:

\[ Q_{\text{NGT}}^{\text{NGT}} = P_{\text{NGT}}^{\text{NGT}}(t)/\eta_{\text{NGT}} \]  

(11)

\[ G_{\text{NGT}}^{\text{NGT}} = E_{\text{NGT}}^{\text{NGT}}*P_{\text{NGT}}^{\text{NGT}}(t) \]  

(12)

where, the generated power from natural gas turbine at hour \( t \) is \( P_{\text{NGT}}^{\text{NGT}} \), electrical efficiency of the natural gas unit is \( \eta_{\text{NGT}} \), and \( E_{\text{NGT}}^{\text{NGT}} \) is the CO2 emission from natural gas turbine per kWh of energy production [6,46].

### 3.1.7. Modeling of natural gas fuel cell system (NGFC)

A fuel cell is an electrochemical device that converts the chemical energy from the methane in natural gas into electricity through a chemical reaction with oxygen. Fuel cell system consists of fuel processor, which converts natural gas fuel to hydrogen, fuel cell stack generates DC power from hydrogen and oxygen (air), power conditioner converts DC power to AC power, and heat recovery, which make heat exchanges for useful thermal energy [13]. Similar to natural gas turbine, NGFC is modeled by Eqs. (11) and (12) with using its own parameters designation (i.e. replacing NGT by NGFC).

### 3.1.8. Power converter model

Because of solar PV module, battery, wind turbine, and fuel cell generate DC output power. Therefore, DC/AC and AC/DC converter is required. The used converter must be able to handle the maximum expected power of AC loads (\( P_{\text{inv}}^{\text{inv}} \)). Thus, the inverter rated power (\( P_{\text{inv}} \)) can be calculated from following equation in terms of the inverter efficiency (\( \eta_{\text{inv}} \)).

\[ P_{\text{inv}} = P_{\text{inv}}^{\text{inv}}/\eta_{\text{inv}} \]  

(13)

### 3.2. Load profile

The proposed hybrid micro-grid power system is designed to ensure the power supply to a small village consisting of 10 households, hospital, school, and worship house in each location from selected areas. A remote village in Egypt is simple and does not need large amounts of electrical energy. Mainly, electrical power is used for lighting and electrical home appliances. The details of the electrical load items and its energy consumption is indicated in Table 2. The corresponding hourly daily load demand of the village in the selected areas is illustrated in Fig. 4. Annual average load consumption of the village is 80 kWh/day at maximum load of 9.5 kW.

### 3.3. Overview of ant colony algorithm

Pheromone is a chemical substance left by an ant during its motion path for a food source. Many other ants in the colony have the ability to perceive the pheromone strength. They track the path where the pheromone concentration is strong. The stronger the pheromone level, the shorter the food way is obtained. Herein, ants could find the shortest and quickest path from their colony location up to food source [47–49]. ACA is inspired by M. Dorigo in 1992 from such cooperative solution of ants [35].

While their looking for a food source, ants try to find optimal values (decision variables) to minimize a path (\( J \)). Each path represents a solution to a fitness function \( f(X_i) \) as in Eq. (14).

\[ J = f(X_i) \]  

(14)

The target is to minimize \( J \). With some constraints on the decision variables, the ACA includes the following steps.

#### 3.3.1. Initialization of nodes and optimization parameters

Ants decide the decision variables. The decided solutions for the decision variables are called nodes. Decision variables spread through nodes according to inequality: \( X_i^{\text{min}} \leq X_i \leq X_i^{\text{max}}, i = 1, 2, …, n \). Where, \( X_i \) is is given as in Eq. (15).

\[ X_i^{\text{min}}=P_1 \quad P_2 \quad P_3 \quad \cdots \quad P_n \]  

(15)

In this step, the maximum number of iterations (\( N_{\text{iter}} \)), number of ants (\( N_{\text{ants}} \)), number of decision variables (\( n \)), number of nodes (\( N_{\text{node}} \)), pheromone level \( \tau_{ij}, \alpha, \beta, \) and \( \rho \) are initialized. The nodes are generated at equal spaced points for each decision variable. The maximum nodes distance or path is determined according to Eq. (16).

\[ d_{\text{max}} = \frac{X_i^{\text{max}} - X_i^{\text{min}}}{N_{\text{node}}} \]  

(16)

#### 3.3.2. Searching

An ant searches for a better solution at a specified node limited
by the distance, \(d_{\text{max}}\). The changing of distance in a discrete manner results in a new position or solution for the ant. Each node is varied randomly with a probability. The probability of selecting a node is computed in terms of the pheromone level according to Eq. (17), in which \(\alpha\) and \(\beta\) ranges between [0,1].

\[
P_{ij} = \frac{\tau_{ij}^{\alpha} \eta_{ij}^{\beta}}{\sum_{k=1}^{n} \tau_{ik}^{\alpha} \eta_{ik}^{\beta}}
\]

During the searching process, an ant may find a node with low objective function evaluation. In this case, the ant’s locations coordinates will be changed.

### 3.3.3. New nodes generation

After every search, the ants’ position (nodes) and pheromone level are interchanged. Then, some ants may find positions with low objective function estimation. Herein, the ants with inappropriate nodes will be replaced by new nodes.

### 3.3.4. Pheromone level updates

For every iteration, the nodes are updated according to pheromone level. The pheromone level digression is given in Eq. (18).

\[
\Delta \tau_{ij}^{k} = \Delta \tau_{ij}^{k-1} + \frac{f_{\text{min}}(X_t)}{f(X_t)} \quad \forall \, i \in N_{\text{node}}, j \in n
\]

Where, \(f_{\text{min}}(X_t)\) is the minimum objective function estimation ever found during an iteration. Finally, the pheromone level is traversed with the new updated values given in Eq. (19).

\[
\tau_{ij}^{k} = \rho \tau_{ij}^{k-1} + \Delta \tau_{ij}^{k} \quad \forall \, i \in N_{\text{node}}, \, j \in n
\]

### 3.3.5. Convergence or end condition checking

The process continues till all ants choose the same path. The algorithm is terminated if a maximum number of iterations are completed or the objective function estimation reaches a minimal threshold changes during iteration. Fig. 5, in the next section, shows how the ACA is employed to solve HMG optimal sizing and configuration.

### 4. Problem formulation

The HMG system economic feasibility problem includes economic and environmental aspects. In addition, it includes objective functions subjected to constraints of all system. The rating of PV, natural gas turbine, biomass gasifier, natural gas fuel cell, diesel generator, and number of wind turbines are the decision variables of the optimization problem.

#### 4.1. Economic and environmental objective functions

The developed procedure is to minimize the objective function \(J\) as given in Eqs. (20–22). It minimizes the price of electricity (COE), green house emissions (GHG), or both. The first objective function \(f_1\) covers the initial, operational and maintenance, and replacement costs of all generating units. The second objective function \(f_2\) covers CO2 emissions of all renewable and DERs generating units.

\[
J = \min(f_1, f_2)
\]

\[
f_1 = \sum_{t \in T} \text{COE}(X_t) \quad \forall \, t \in T
\]

\[
f_2 = \sum_{i \in G} \text{GHG}(X_i) \quad \forall \, i \in G
\]

#### 4.1.1. Cost function of price of energy (COE)

The target of objective function to minimize the cost of energy (COE), which is function in total annual cost \((C_{\text{Ta}})\).

\[
\text{COE} = \frac{C_{\text{Ta}}}{E_{\text{Ta}}}
\]

Where, \(E_{\text{Ta}}\) is the annual demand load in kWh. The total net preset cost is calculated according to Eq. (24).

\[
\text{TNPC} = \frac{C_{\text{Ta}}}{\text{CRF}}
\]

Where

\[
C_{\text{Ta}} = C_{\text{int}} \times \text{CRF} + C_{\text{OM}} \times \text{PWF} + C_{\text{rep}} \times \text{RF}
\]

where \(C_{\text{int}}, C_{\text{OM}}, C_{\text{rep}}:\) initial, operating and maintenance, and replacement costs of HMG system respectively.

\(\text{CRF, PWF, RF}:\) the capital recovery, present worth of maintenance and replacement factors.

The \(\text{CRF, PWF, RF}\) are presented in Eqs. (26–28) in terms of interest rate \((i)\) and inflation rate \((l)\) to give the current value of the hybrid system components at given time period [50].

\[
\text{CRF} = \frac{i(1+i)^N}{(1+i)^N - 1}
\]
\[ PWF = \left( \frac{1 + i}{1 + i} \right) \left\{ \frac{1}{1 - \left( \frac{1 + i}{1 + i} \right)^N} \right\} \]  

(27)

\[ RF = \left( \frac{1 + i}{1 + i} \right)^N \]  

(28)

Herein, initial costs of PV, wind turbine, diesel generator, battery bank, biomass generator, natural gas turbine and natural gas fuel cell are presented in Eq. (29).

\[ C_{\text{int}} = P_{PV} \ast C_{PV} + N_{WT} \ast P_{WT} \ast C_{WT} + P_{dis} \ast C_{dis} + P_{FC} \ast C_{FC} + P_{Bio} \ast C_{Bio} + P_{NGT} \ast C_{NGT} + E_{Batt} \ast C_{Batt} + P_{inv} \ast C_{inv} \]  

(29)

Where,

- \( P_{PV}, P_{WT}, P_{dis}, P_{FC}, P_{Bio}, P_{NGT}, P_{inv} \) : the PV, wind turbine, diesel, fuel cell, biomass, natural gas turbine, and inverter capacities.
- \( C_{PV}, C_{WT}, C_{dis}, C_{FC}, C_{Bio}, C_{NGT}, C_{Batt}, C_{inv} \) : the PV, wind turbine, diesel, fuel cell, biomass, natural gas turbine, and inverter, battery initial costs.
- \( N_{WT} \) : Number of wind turbines
- \( E_{Batt} \) : Battery capacity (kWh)

Operating and maintenance costs (\( C_{OM} \)) include the cost of fuel (\( C_f \)) consumed by different energy sources and maintenance cost (\( C_m \)) of each source depending on the operating hours and...
generated energy in kWh along lifetime of the system as illustrated in Eqs. (30–35).

\[ C_{OM} = C_m + C_f \]  
\[ (30) \]

Where

\[ C_m = C_m^i \times \sum_{t=1}^{8640} P_j(t) \]  
\[ (31) \]

where, \( j \) is the source number (\( j = 1 \) to 7), ignoring the maintenance cost of the battery, \( C_m^i \) is the maintenance cost for each source in $/kWh, \( P_j(t) \) is the energy produced in kWh from each source at time \( t \). In proposed system, there are four sources consumed fuel during their operation. These sources are diesel, biomass, fuel cell and natural gas turbine. Thus, the total net present value of the fuel for these sources \( C_f \) can be obtained from following formula:

\[ C_f = \left( C_{a, dis}^f + C_{Bio}^f + C_{FC}^f + C_{NGT}^f \right) \times PWF \]  
\[ (32) \]

where, \( C_{a, dis}^f \) is the annual cost of diesel fuel consumption which calculated by multiplying Eq. (8) by the number of operating hours of diesel generator. The annual cost of fuel consumption of biomass, fuel cell, and natural gas turbine generators can be determined from the following formulas:

\[ C_{Bio}^f = \frac{E_{Bio}}{\eta_{Bio}} \times f_{Bio} \]  
\[ (33) \]

\[ C_{FC}^f = \frac{\sum_{t=1}^{8640} P_{FC}(t) \times N_{FC}}{\eta_{FC}} \times f_{FC} \]  
\[ (34) \]

\[ C_{NGT}^f = \frac{\sum_{t=1}^{8640} P_{NGT}(t) \times N_{NGT}}{\eta_{NGT}} \times f_{NGT} \]  
\[ (35) \]

where, \( \eta_{Bio}, \eta_{FC}, \eta_{NGT} \) are electrical efficiencies of biomass, fuel cell, and natural gas turbine generators respectively. \( f_{Bio}, f_{FC} \) and \( f_{NGT} \) are fuel price ($/kWh) of biomass, fuel cell, and natural gas turbine generators, respectively. Regarding the replacement cost \( (C_{rep}) \), it is assumed that lifetime of all system components are the same as the system lifetime (i.e. 25 years) except battery that of which is

---

**Fig. 6.** Battery and diesel flow chart using BOACA.
assumed to be 5 years. Therefore, the replacement cost of the battery \(C_{\text{Batt}}^{\text{rep}}\) along the system lifetime taking into account the present worth factor can be obtained from Eq. (36) with considering replacement factor \((RF)\) in Eq. (28) [51].

\[
C_{\text{Batt}}^{\text{rep}} = C_{\text{Batt, init}} \left[ \left(1 + \frac{i}{1+i} \right)^5 + \left(1 + \frac{i}{1+i} \right)^{10} + \left(1 + \frac{i}{1+i} \right)^{20} \right]
\]

where, \(C_{\text{Batt, init}} = E_{\text{Batt}} \times C_{\text{Batt}}\) is the initial cost of the first purchased battery bank, \(i\) is the inflation rate (30%), and \(i\) is the interest rate (15%) as given in Ref. [52].

4.1.2. Objective function of greenhouse gas emissions (GHG)

The main target of this objective function is to minimize the greenhouse gas emissions to get environmental friendly hybrid power generation system along with its lifetime. The total annual GHG emissions can be obtained from following equation:

\[
\text{GHG} = \text{EM}_j \times \sum_{t=1}^{8640} P_j(t) \quad \forall j \in G
\]

Where, \(j\) is the source number, \(EM_j\) is the CO2 emissions in kg/kWh for each source \(P_j\). According life cycle assessment (LCA) technique, the GHG emissions from all sources are estimated. There are considerable GHG emissions from all renewable energy sources if we take into consideration manufacturing, material procurement, and transportation of these sources despite of some people considering them as zero-emission sources during their operation [53].

4.2. Analysis of hybrid system reliability

For load demands, it is important to take into consideration the hybrid configuration, which fulfills the optimal economic and environmental objective function. Meanwhile, such optimal configuration can meet load demand without any shortage in electrical power continuously during the lifetime of the system components. The loss of power supply probability (LPSP) is an important parameter for measuring the HMG system reliability. LPSP is a relation between the shortage in energy demands when the generated and storage energy is less than the load demand divide by the total load demand as in Eq. (38).

\[
\text{LPSP} = \frac{\sum_{t=1}^{8640} (E_i(t) - E_s(t))}{\sum_{t=1}^{8640} E_i(t)} \quad \forall t \in T
\]

Where,

\(E_i\): Demand load in kWh \\
\(E_s\): Total sources generation in kWh

4.3. Constraints

4.3.1. Constraints of energy resources

To treat the HMG power capacity that should be as high as possible to ensure load demands, the constraints of energy sources for HMG system are defined by following formula.

\[
\sum_{t=1}^{8640} \left( P_{\text{PV}}(t) + P_{\text{W}}(t) + P_{\text{dis}}(t) + P_{\text{biomass}}(t) + P_{\text{NGFC}}(t) + P_{\text{NGT}}(t) \right)
\geq \sum_{i=1}^{8640} E_i(t) \eta_{\text{inv}}
\]

Constraints of generated power and load demand \(E_i\) are based on limitation of components size of the HMG system and number of households. Table 3 shows the boundaries of the capacity constraints.

4.3.2. Battery power management constraints

Excess electricity power generation system is used to charge the battery bank whereas the shortage of energy can be supplied from battery bank or diesel generator according to Eqs.(40) and (41) respectively.

\[
P_g(t) = \frac{E_i(t)}{\eta_{\text{inv}}} - (P_{\text{PV}}(t) + P_{\text{W}}(t) + P_{\text{dis}}(t) + P_{\text{biomass}}(t) + P_{\text{NGFC}}(t) + P_{\text{NGT}}(t))
\]

\[
P_{\text{batt}}(t) = \begin{cases} \frac{P_{\text{batt}}(t - 1) \times (1 - \sigma) - P_g(t) \times \eta_{\text{Batt}}}{P_{\text{batt}}(t - 1) \times (1 - \sigma)} \geq P_g(t) & \text{if} \quad P_g(t) < 0 \\ P_g(t) \geq 0 
\end{cases}
\]

where, \(P_g(t)\) is the shortage or the excess energy, \(E_i\) is power demand, \(P_{\text{batt}}(t - 1)\) and \(P_{\text{batt}}(t)\) are the residual sums of charge in the battery at times \(t - 1\) and \(t\) respectively. Assuming that each battery has an initial charge of 20% of its rated capacity, the efficiency of charging the battery bank is \(\eta_{\text{Batt}}\) and the rate of self-discharge of the battery bank at each hour is designated \(\sigma\). To reduce the risk of shortage of the storage battery, minimize number of batteries, and reduce the need of diesel generator-which leads to minimize the net system cost and environmental impacts-the other energy resources such as biomass, fuel cell, and natural gas turbine are used. The charge in the battery is governed by minimum and maximum capacity of storage battery, \(E_{\text{bmin}}\) and \(E_{\text{bmax}}\), as specified in Eqs. (42) and (43), respectively.

\[
E_{\text{bmin}} \leq E_{\text{batt}}(t) \leq E_{\text{bmax}}
\]

\[
E_{\text{bmin}} = (1 - \text{DOD}) \times E_{\text{bmax}}
\]

4.4. Implementation of ant colony algorithm

Optimal planning of microgrid system configuration provides an effective way to decrease COE and GHG emissions and consequently saves net annual present cost. Herein, the developed work presents the optimal planning configuration for HMG systems and assesses their corresponding size. To prove the economic and environmental viewpoints, it is required to run bi-objective optimization algorithm analysis and estimate the COE and GHG emissions due to the optimal configuration planning process. Fig. 5 shows a flow chart of the developed bi-objective ant colony algorithm (BOACA) to solve HMG systems configuration problems. In this study, the BOACA is developed specifically to manage optimal configuration planning and sizing of HMG systems. The testing procedure starts by stochastic evaluation of DERS with multiple fuel options for the studied households’ dwellings environment. The
goal is to minimize total COE, GHG emissions, and a compromising approach to minimize both COE and GHG emissions.

Due to intermitted nature of renewable-based resources such as wind and PV, variation in the output power results in complicated power strategy management for HMG systems. Such power management is highly required to meet load demand distribution. In addition, limited capacity of renewable DERS does not allow immediate increase in the output power to match load demand. Hence, having a strategy for power management is essential for HMG systems. The following cases are deemed out in the optimization process of the developed BOACA.

Case 1: renewable-based resources and other DERS can provide sufficient energy amount for the HMG system. Herein, the extra power is fed to the battery bank as shown in Fig. 6.

Case 2: Similar to case 1, however the energy produced by renewable-based resources and DERS is greater than load demand and battery bank charging capacity. Herein, the surplus power is consumed in a dump load.

Case 3: renewable-based resources and DERS are unable to feed sufficient power to load demands due to DERS capacity constraints. Thus, the priority is to discharge battery bank as in Fig. 6.

Case 4: renewable-based resources and DERS are unable to feed sufficient power to load demands due to DERS capacity constraints and the battery bank energy is consumed. Thereafter, the diesel generator is switched on to match load demands as depicted in Fig. 6.

In all cases, the available renewable-based resources and dispatchable DERS power supplies priority are decided by the BOACA according to the desired objective function, e.g. COE, GHG, or combined solution. Meanwhile, the battery status to discharge or charge electric current is checked.

4.5. Bi-objective competition algorithm

The motivation to use solution that is compromised solutions are not provided by software packages such as HOMER. The combined solution is chosen in this work to compromise between two solutions. In this scenario, both of price of electricity (COE) and GHG emissions objectives are considered to get a single compromised solution to get a single compromised solution for each of the considered areas. The two objectives can be converted as optimal solutions of the individual decision variables and the objectives cannot be the same. A weighting factors summation method can be utilized to transform the bi-objective issue of the problem into a single objective aspect. However, weighting factors are significantly dependent on importance of the different objectives.

In this work, the compromised solution depends on minimizing gap among possible solutions. It is called Utopia point as shown in Fig. 7 [6,54]. This point may not be feasible as it decreases both objectives altogether. The obtained solutions from previous studied scenarios (e.g. COE only and GHG emissions only) will be used to set limits of the individual objectives. For instance, the optimal solution of COE sets the lower limits (COE\(_{min}\)) and maximum or upper limits on greenhouse gas emissions (GHG\(_{max}\)). On the other hand, the optimal solution of GHG sets the upper limits on COE (COE\(_{max}\)) and lower limits on GHG (GHG\(_{min}\)). The upper and lower boundary conditions are utilized to portray individual objectives membership functions as in Fig. 8. For each objective, the membership functions of COE and GHG are given in Eqs. (44) and (45) respectively.

Finally, the compromised solution is obtained by minimizing the gap among the possible solutions to the Utopia point (COE\(_{min}\), GHG\(_{min}\)). The Euclidean gap of the candidate or feasible solution (COE, GHG) to the ideal Utopia point is given as in Eq. (46).

\[
\|S\| = \sqrt{(1 - \mu(f_1))^2 + (1 - \mu(f_2))^2}
\]

5. Results and discussions

The developed BOACA is applied to design the optimal HMG system configuration and sizing for a small isolated hybrid PV/wind/biomass/NGFC/NGT of three isolated villages in three governorates. The meteorological conditions are considered separately for each area. Based on the nature of particular locations, they have enough raw stock to build a biomass gasifier. The main straw at these areas in Egypt is related to rice, wheat, and corn crops. More than 63.7% of biomass quantity could be extracted from rice and corn [43]. Wheat straw is fed directly to domestic cattle. However, corn and rice straw is wasted without any economical use. Normally, farmers burn it in a manner increases the environmental pollution. Based on the following economic and environmental scenarios and the biomass generator prices, the results in this study could provide the farmers a notion to use rice or corn residues to produce electricity. Table 4 gives the parameters for various costs.
Table 4
Technical and economic parameters of system components.

<table>
<thead>
<tr>
<th>Load type</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
<tr>
<td>PV</td>
<td></td>
<td></td>
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<tr>
<td>Life time</td>
<td>25</td>
<td>year</td>
</tr>
<tr>
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</tr>
<tr>
<td>Operational &amp; maintenance cost</td>
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<td>$/kW</td>
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<td>CO2 emissions</td>
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<td>Kg/kWh</td>
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<td>Wind turbine</td>
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<td></td>
</tr>
<tr>
<td>Life time</td>
<td>25</td>
<td>year</td>
</tr>
<tr>
<td>Initial cost</td>
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<td>$/kW</td>
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<tr>
<td>Operational &amp; maintenance cost</td>
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<td>$/kW</td>
</tr>
<tr>
<td>CO2 emissions</td>
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<td>Battery</td>
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<td>year</td>
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<tr>
<td>Efficiency</td>
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<td>%</td>
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<tr>
<td>Initial cost</td>
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</tr>
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</tr>
<tr>
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<tr>
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<td>CO2 emissions</td>
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<td>Efficiency</td>
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<td>%</td>
</tr>
<tr>
<td>Natural gas turbine</td>
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<td>CO2 emissions</td>
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<td>Efficiency</td>
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<td>%</td>
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<td>h</td>
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<td>Operational &amp; maintenance cost</td>
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<tr>
<td>CO2 emissions</td>
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<td>Kg/kWh</td>
</tr>
<tr>
<td>Converter</td>
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<td></td>
</tr>
<tr>
<td>Life time</td>
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<td>year</td>
</tr>
<tr>
<td>Initial cost</td>
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</tr>
<tr>
<td>Efficiency</td>
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<td>%</td>
</tr>
<tr>
<td>Others</td>
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<tr>
<td>Project life time</td>
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<td>Year</td>
</tr>
<tr>
<td>Interest rate</td>
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<td>%</td>
</tr>
<tr>
<td>Inflation rate</td>
<td>30.0</td>
<td>%</td>
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</table>

and CO₂ emissions. The evaluation of the different resources options is given in discrete values with a step of 0.5 kW. The estimation of wind turbine is given in number with step of unity. The characteristics of the selected wind turbine are given in Appendix (b).

For each area, three cases with multiple fuel options are investigated in this work:

1) Economical approach, which minimizes total costs of energy only.
2) Environmental approach, which minimizes total CO₂ emissions.
3) Combined solution, which compromises between the economic and environmental objectives.

Different optimization techniques are used in order to obtain the optimal configuration of HMG system that meets the load demand in different configurations of operation. In order to prove the effectiveness of the developed BOACA, the obtained results are compared with genetic algorithm (GA), particle swarm optimization (PSO), and HOMER. The developed BOACA, GA, PSO have been implemented for the same load profile via MATLAB 2015 with 1 h simulation step. For sake of comparison, maximum capacity of various renewable and distributed DERs is set to 5 kW and the maximum number of wind turbine is set to five units for all cases. The parameters of the developed BOACA are given Appendix (a).

5.1. Results of scenario 1

The optimal configuration of the system shown in Fig. 1 is investigated in this scenario. The feasible optimal results are given in Table 5. The COE is defined as the objective function. To prove the reliability of the developed system configuration, the LPSP is calculated.

Both GA and BOACA chose 5 kW for PV. However, PSO chose 4 kW. The corresponding optimal wind energy power are 3, 4, 4 kW for GA, PSO, and BOACA respectively. To meet load demand with DERs capacity limitations, these choices determine the total number of batteries. It is inferred that the developed BOACA gives satisfactory results. It records the least COE and TNPC values. The corresponding annual energy production percentage for each area using BOACA is illustrated in Fig. 9. As expected from weather data in Table 1, Saint Catherine, located in the northeastern area, shows the lowest wind energy percentage with 5%. The reduction in renewable energy sources in Saint Catherine raises the TNPC to 163551$. The results reflect that diesel generator is not compulsory option with such DERs resources. The other two areas show approximately the same energy production percentage with high percentage of natural gas based DERs resources. Natural gas turbine and fuel cell based generators records 59% and 12% respectively. Therefore, using multiple fuel options in addition to renewable energy resources can enhance the economical saving for Kharga and Quseer with TNPC equals 163551$. For all areas, the calculated LPSP is zero. The spectacular appeal in using the available multiple fuels with renewable energy resources is the reduction in using battery storage banks and diesel generators. Reduction in using batteries confirms that there is no replacement required as other generators have the same project lifetime. In addition, reduction in using diesel generator decreases the overall HMG system emission. Therefore, the obtained results using BOACA may be considered the

Fig. 8. bi-objective solution membership functions.
optimal configuration for the studied areas. BOACA converges fast compared to HOMER. For instance, the objective function against iteration number is shown in Fig. 10 for Kharga. For BOACA, the first 15 iterations take around 127s with a computer having CPU intel-core of i3 with 3.6 GHz speed. HOMER takes tens of minutes to perform the same job. Therefore, the developed meta-heuristic algorithms reduce the total simulation time.

5.2. Results of scenario 2

In this scenario, the objective is to minimize GHG emissions. The results of this scenario are given in Table 6. The developed
algorithms are applied to select the optimal HMG configuration for each area. Fig. 11 shows the annualized energy production percentage for each area using BOACA. In order to confirm the reliability and effectiveness of the developed BOACA algorithm, a comparison was made among the other algorithms to solve HMG system optimal configuration problem. From the data given in Table 5, it is worth to note that BOACA competes the other algorithms. It gives the minimal results for two areas among the three investigated areas. The performance of the objective function convergence against the iteration number is depicted in Fig. 12. The first eight iterations take about 106s.

For Saint Catherine, the total GHG emissions is 4706 kg/year. This corresponding to 73.45% reduction in GHG emissions compared to the first scenario. For Kharga and Quseer, the GHG reduction achieves 74.45% as compared with results in previous scenario. Biomass generators are notable in reducing total GHG emissions, as they are considered neutral, i.e. the CO2 emissions absorbed during its lifetime is released during burning. It is clear that the battery bank contributes with a noticeable yearly percentage. It records around 17% for all areas as illustrated in Fig. 11. Therefore, the overall costs of COE and TNPC are increased as indicated in Table 5, which represents the main negative side of this scenario as public people in our developed country cannot pay this amount of money for purchasing electrical energy.

5.3. Results of scenario 3

For utilities which are interested in minimizing both economic and environmental aspects; this scenario provides the compromised solution. The feasible optimal results are given Table 7. In this scenario, it is inferred that the developed BOACA gives satisfactory results. Not only does it give a compromised solution between cost and GHG emissions, but also it gives a compromised solution for the three studied areas. Actually, this is expected solution due to the close characteristics of weather conditions as given in Table 1. In addition, the fuel costs and carbon footprints of other DERs options are the same for all areas. The corresponding yearly energy production is illustrated in Fig. 13. It can be noted that major renewable energy contribution comes from solar PV. The biomass energy generator and NGT contributes evenly in the annualized energy production. Compared to scenario 2, the system COE is reduced by about 95% using Kharga results as in Table 8. On the other hand, the total system emissions are reduced by 33.15% compared to scenario 1. BOACA converges fast in this scenario as in Fig. 14. The first 18 iterations takes about 177s.

The carbon footprints for each DER is different. Therefore, based on DERs type and the load parameters given in Table 2, utilization of multiple fuel options in addition to renewable energy resources can enhance both the economical saving and environmental GHG emissions reduction for all areas. This scenario contains the merits of scenario 1 with reduction in using battery storage banks and diesel generators. In addition, the calculated LSPS is found to be zero. This confirms that no replacement costs are required for the DERs unit options for the HMG system.

5.3.1. Effectiveness of the developed BOACA

The effectiveness of the developed BOACA is given in Table 9 for different areas with different optimization algorithms. For instance,
the study in Ref. [3] is done using particle swarm optimization (PSO) for several cities. In Ref. [3], only renewables, diesel, and energy storage were used. The harmony search algorithm was employed in Ref. [39]. However, it shows big value regarding the TNPC. In [57], the levelised COE was not given. The TNPC obtained in [57] is slightly higher than the value obtained by the developed BOACA. Even the results are system level and depend on the load profile; the results show that the developed BOACA is competitive to the other algorithms developed in the literature with minimizing both COE and GHG emissions.

5.3.2. Impact of HMG system parameters variation

The parameters sensitivity was extended in order to characterize the impact on the COE and GHG emissions, which were computed using BOACA. In the developed combined solution, parameters variation affects the Utopia point directly. Utopia point has an impact implicitly on both COE and GHG emissions differ-
ently. Based on the optimal points in Table 7, PV power, wind turbine number, biomass generator, natural gas micro-turbine, and load demand variation were selected to investigate parameters sensitivity on COE and GHG emissions. For sensitivity analysis, the parameters variation starts from 50% to 150% as shown in Figs. 15 and 16. In Fig. 15, it can be noticed that COE is more affected by a variation in load demands as load variation goes more than 100%. It can be observed that COE becomes sensitive and larger for lower values of biomass and NGT output powers. The reason for this is related to the increased dependence on the battery bank.

In Fig. 16, it can be observed load demand and NGT variations have a significant impact upon GHG emissions. As expected, other parameters variations such as biomass generator, PV, and number of wind turbines are approximately neutral regarding GHG emissions. However, the price of electricity and GHG emissions becomes more stable as the number of renewable resources increases.

5.3.3. Impact of failure of one generating unit

In this part, the results due to failure of a generating unit within the HMG system are considered to confirm the reliability of the investigated HMG system. For instance, failure of PV source during January is common in the middle and northern parts in Egypt. Failure in any generating unit creates imbalance in meeting load demands in any HMG system. Fig. 17 shows the energy production percentage for one week in the beginning of January. Meanwhile, the other optimized parameters are kept the same. It can be noticed from Fig. 17 that energy production from for both NGT and biomass generator of HMG system without PV energy are 45% against 36% in case of existing PV energy. Due to capacity limitations of NGT and biomass generator, battery banks have to contribute by about 3% during this period. In addition, due to using battery and more usage of NGT and biomass gasifier, COE increases from 1.082 to 1.192$/MWh, which makes the annualized somewhat costlier. The total CO₂ emissions varies slightly form 11833 to 11823 kg.

![Fig. 14. Objective function convergence variation for Kharga using BOACA for combined solution.](image)

![Fig. 15. Sensitivity of COE against parameter variation.](image)

### Table 9: Effectiveness of BOACA

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>City A</td>
<td>1.082</td>
<td>1.87</td>
<td>0.35</td>
<td>0.12</td>
</tr>
<tr>
<td>City B</td>
<td>121589.67</td>
<td>131129</td>
<td>1,088,442.67</td>
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</tr>
</tbody>
</table>

50 60 70 80 90 100 110 120 130 140 150

![Chart 1](chart1.png)

![Chart 2](chart2.png)
5.3.4. Impact of shifting PV operating point

In this section, the behavior of the developed HMG system is tested with shifting the MPPT point of the solar irradiation. Fig. 18a shows an optimal typical day in average PV capacity, load demand, and the dump load profiles without shifting the PV operating point. The target of this section is to examine the impact of shifting the PV operating point away from the maximum power point (MPP) to reduce the generated power. Meanwhile, all optimized parameters capacity is kept the same.

The study of Fig. 18a shows that the dump load is high from 7am to 6pm. Major role of this behavior is due to abundant solar irradiation. Besides, peak load demand takes place from 11am to 1pm. The investigation of the renewable energy resources shows that power delivered to the dump load could be reduced if the PV operating point is moved away from the MPP operation. Controlling the duty cycle of a simple DC/DC boost converter can perform the shifting of the PV operating point from the MPP operation. This is done in Fig. 18b. The operating point of the PV module was shift to a minimum value from 7 to 10am and from 2 to 6pm. Fig. 18b shows the improvement in dump load profile due to shifting the PV maximum power point. It is obvious that the power consumed on the dump load is reduced and the target of shifting the PV operating point was confirmed. Table 10 shows the effect of shifting the MPP upon the COE and GHG emissions. It is observed the GHG emission is slightly decreased.

5.3.5. Robustness test

As meta-heuristic algorithms are stochastic, every run starts from different operating points. Therefore in order to confirm the effectiveness of the developed BOACA, forty five independent runs have been carried out. Fifteen runs have been performed for each area. The results are compared with another 45 independent runs performed by GA and PSO. Table 11 shows average, maximum, minimum, standard deviation, and chosen combined solution number of iteration for each area respectively. It is clear that the developed BOACA gives satisfactory results for the Utopia point and its implicit parameters. The BOACA gives the minimum standard deviation results. The results in Table 11 shows that the chosen optimized combined solution can be considered the best solution and the effectiveness of the developed BOACA is affirmed.

6. Conclusions

In this research, a hybrid microgrid (HMG) system for islanded
sites is investigated in an optimal manner. A bi-objective problem is proposed to decide the optimal yearly renewable and DERs outputs to minimize the cost of electricity (COE) and greenhouse gas (GHG) emissions. Simulation results show that the developed method is effective to offer an optimal configuration for all investigated areas and different objective scenarios for economic and environmental perspectives. For the investigated areas, the results show that PV

![Graph](image)

**Fig. 18.** Annualized energy production percentage with doubling solar irradiation: (a) Before shifting PV operating point. (b) After Shifting PV operating point.

<table>
<thead>
<tr>
<th>Table 10</th>
<th>Results for combined COE and GHG minimization with shifting the PV irradiation.</th>
</tr>
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<tbody>
<tr>
<td>BOACA</td>
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<table>
<thead>
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<th>Table 11</th>
<th>Statistical results for the combined COE and GHG solution.</th>
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<tr>
<td>BOACA</td>
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</tr>
<tr>
<td>Utopia point</td>
<td>COE ($/kWh)</td>
</tr>
<tr>
<td>Utopia point</td>
<td>TNPC ($)</td>
</tr>
<tr>
<td>GA</td>
<td>COE ($/kWh)</td>
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<tr>
<td>GA</td>
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<tr>
<td>PSO</td>
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</tr>
<tr>
<td>PSO</td>
<td>TNPC ($)</td>
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<tr>
<td>PSO</td>
<td>COE ($/kWh)</td>
</tr>
<tr>
<td>PSO</td>
<td>TNPC ($)</td>
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<td>PSO</td>
<td>COE ($/kWh)</td>
</tr>
<tr>
<td>PSO</td>
<td>TNPC ($)</td>
</tr>
</tbody>
</table>
generator and natural gas turbine are superior to biomass generator in reducing COE objective. Also, biomass generator and battery bank operation are superior to natural gas turbine and PV generator in reducing GHG emissions. The economic feasibility analysis illustrates that the existence of DERs in addition to renewable resources can lead to saving/reduction in total costs and decrease in GHG emissions. The mathematical modeling of the individual components used in this study has been briefly discussed. Then, the operational strategy and BOACA implementation steps have been introduced. The performance of the investigated HMG system configuration is considered by taking into account the failure of one generating unit. From the above development, discussion, and comparison results, the following conclusions are drawn. (1) Implementation of HMG system can be considered as a promising solution for islanded areas electrifications for the investigated locations. (2) The developed BOACA algorithm offers optimal HMG system configuration and sizing to be evaluated in an economic and high-qualified environmental manner compared to HOMER, GA, and PSO. (3) The developed HMG system can be also regarded as a starting point or supportive tool to enhance electrification of islanded areas and design futuristic and efficient projects faster. For future work, an economic feasibility study with considering stochastic behavior of renewable energy resources with multiple fuel options are to be investigated. Besides, modern techniques such as converting energy wasted in dump load into hydrogen gas or using pump to restore water in a reservoir to improve agricultural activities and regenerate electrical energy during rush hours are to be considered.

Appendix

(a) AC constants: number of ants = 60; number of nodes = 2000; alpha (α) = 0.5, beta (β) = 0.5; number of iteration = 100; rho (ρ) = 0.1.

(b) Wind turbine parameters: swept area = 19.63 m², efficiency = 95%, Blades diameter = 2.5 m, cut out speed = 16 m/s, cut in speed = 2.5 m/s, rated speed = 7 m/s, rated power = 0.3 kW.

References


References


