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Optimal Sizing and Design of Isolated Micro-Grid systems

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Abstract

Micro-grid and standalone schemes are emerging as a viable mixed source of electricity due to interconnected costly central power plants and associated faults as well as brownouts and blackouts in additions to costly fuels. Micro-Grid (MG) is gaining very importance to avoid or decrease these problems. The objective of this paper is to design an optimal sizing and energy management scheme of an isolated MG. The MG is suggested to supply load located in El-shorouk Academy, Egypt between 30.119 latitudes and 31.605 longitudes. The components of the MG are selected and designed for achieving minimum Total Investment Cost (TIC) with CO_2 emissions limitations. This is accomplished by a search and optimization MATLAB code used with Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) techniques. The use of Diesel Generators (DGs) is minimized by limiting the gaseous CO_2 emissions as per targeted allowable amount. A comparison is accomplished for investigating the CO_2 emissions constraints effects on the TIC in $/year and annual cost of energy in $/kWh. The obtained results verified and demonstrated that the designed MG configuration scheme is able to feed the energy entailed by the suggested load cost effectively and environmental friendly.

Keywords

Micro-Grid (MG); Optimal Design; Optimal Control; GA; PSO.

Nomenclature

BFOA	Bacterial Foraging Optimization Algorithm
DER	Distributed Energy Resources
EPF	Energy Pattern Factor
FC	Fuel Consumption
ES	Energy Storage
GA	Genetic Algorithm
MG	Micro-Grid
MPPT	Maximum Power Point Tracker
PSO	Particle Swarm Optimization
PV	Photovoltaic
SOC	State of Charge

TIC	Total Investment Cost
WT	Total Investment Cost

1. Introduction

Micro Grid is a standalone “a local energy provider which reduces energy expense and gas emissions by using Distributed Energy Resources (DERs)”. MG is treated to be a promising choice or even an alternative to existing centralized or traditional grids (Zhang, 2013). MGs apply a diversity of Distributed Generation units. These units includes photovoltaic (PV) modules, Wind Turbines (WT) and energy storage (ES) such as batteries (Shi, Xie, Chu, &, Gadh, 2014).

It is noted that very large number of population in the developing regions currently lose grid based electric current services. MGs represent an important option for reducing the electricity gap in very parts of developing world in the case of grid extension is unpractical (Zhang, 2013).

Proper selection of DERs and optimal sizing for them, for specific goal or objective, are challenging and very important tasks in the designing of isolated MGs. This is because the coordination between the MG units with adds of constraints is complicated (Hassanzadehfard, Tafreshi, & Hakimi, 2011). A nonlinear optimization problem is to be formulated using the basic problem. This optimization problem can be then solved by a desired suitable optimising technique.

There are number of optimization techniques which are used for the design of MGs (Paudel, Shrestha, & Adhikari, 2011) such as the graphical construction methods (Borowy & Salameh, 1996), linear programming (Chedid & Rehman, 1997), iterative approach (Yang & Zhou, 2007), GA (Zhou, Yang, & Fang, 2008), and bacterial foraging (Noroozian & Vahedi, 2010) and so on. The goal for each designer is to determine the best optimal objective/fitness function value for a given configuration whichever the optimization method.

Rui Huang et al. In (Huang, Wang, Chu, Gadh, & Song, 2014) studied and proposed an approach to find the optimal placements and sizes of a MG components. To solve the optimization problem, GA is used and compared with a mathematical optimization method (nonlinear programming). A comprehensive objective function with practical constraints which take all the important factors that will affect the reliability of the power grid, into account is proposed. The analysis on results shows that GA maintains a delicate balance between performance and complexity. It is concluded that GA performs better not only in accuracy, stability, but also in computation time. Authors of (Huang, Wang, Chu, Gadh, & Song, 2014) did not take the constraints on dynamical power flow into consideration when designing the new power system. A more comprehensive optimization problem need to be studied and solved thoroughly.

In (Tabatabaei & Vahidi, 2013) proposed a model for setting the optimal operation of a MG. Diversity of distributed generation sources that usually used in MGs are obtained by their proposed optimization problem. Constraints are taken into considerations, in the proposed optimization problem, to reflect a number of limitations which is found in a MG systems. Environmental costs have been also considered in the optimization problem. For minimizing the defined objective/fitness function by considering network and load limitations, a new evolutionary algorithm known as Bacterial Foraging Optimization Algorithm (BFOA) is applied. Although the used technique is a new one, it has some disadvantages such as large number of parameters and complexity in design.

In (Mohamed & Koivo, 2007) suggested a generalized formulation for obtaining the optimal operation strategy and cost minimization scheme for a MG. The MG components from actual manufacturer data are constructed before the optimization of the MG itself. The suggested objective/fitness function considers the costs of the emissions, and the operation & maintenance costs. The optimization method is aimed for reducing the cost objective/fitness function of the system while constraining the objective for meeting the load demand profile and safety of the system. Authors of (Mohamed & Koivo, 2007) did not put the environmental impacts into consideration which should be considered to reduce the emissions level. The proposed cost function takes into consideration the costs of the emissions NO_x, SO_2, and CO_2 as well as the operation and maintenance costs but the the replacement cost is not considered. The optimization aims to minimize the cost function of the system while constraining it to meet the customer demand and safety of the system without taking the environmental constraints into consideration.

Recently, it is needful to obtain a flexible generalized approach or methodology for any kind of MG design of higher computational efficiency. In addition, the computational optimization methods which use bio-inspired technologies have been significantly developed in recent years. They can effectively increase the efficiency of MG systems by finding the best configuration for optimizing the economic and technical criteria.

This paper presents a design of an optimal sizing and energy management scheme of an isolated MG components. AMATLAB code is proposed for calculating the energy available from MG generation sources according to meteorological data of the suggested location. The proposed optimization scheme has the advantages that it is simple and and can be extended to deal with multi-objective functions besides dealing with more renewable and storage components for the MG. The components of the MG are selected and designed to supply the suggested load under the objective of minimum TIC with CO_2 emissions limitations. The optimization process is carried out via GA and PSO techniques. A comparison is accomplished to investigate the CO2 emissions constraints effects on the TIC in $/year and annual cost of energy in $/kWh. It has been proved that the proposed scheme can robustly and efficiently obtain the optimal MG configuration which is Eco-friendly and has great economic benefits. Consequently, this research reveals that the MG will operate successfully as an isolated controllable power generation unit for supporting the utility as well as reduces the dependency on the main grid and increases the market penetration of the MG system or MG sources. Accordingly, it minimizes the problems associated with central power plants such as power blackout and limitations of fossil fuels.

The rest of this article is organized as follows: Description and modelling of the components for the MG are introduced in Section 2. Fitness function and constraints are presented and modeled in Section 3. Section 4 describes proposed optimization procedures and a case study. Section 5 presents simulation results and analysis. Finally conclusion is discussed in Section 6.

2. Complete system modeling

The proposed isolated MG system includes WTs, PVs, batteries, PV controllers, DG units, and inverters. The schematic diagram for the suggested MG system is indicated by Fig. 1. The first step for optimization process is to model the MG components used to supply the load. In the following sections, a modeling description of the components of the complete system is demonstrated.

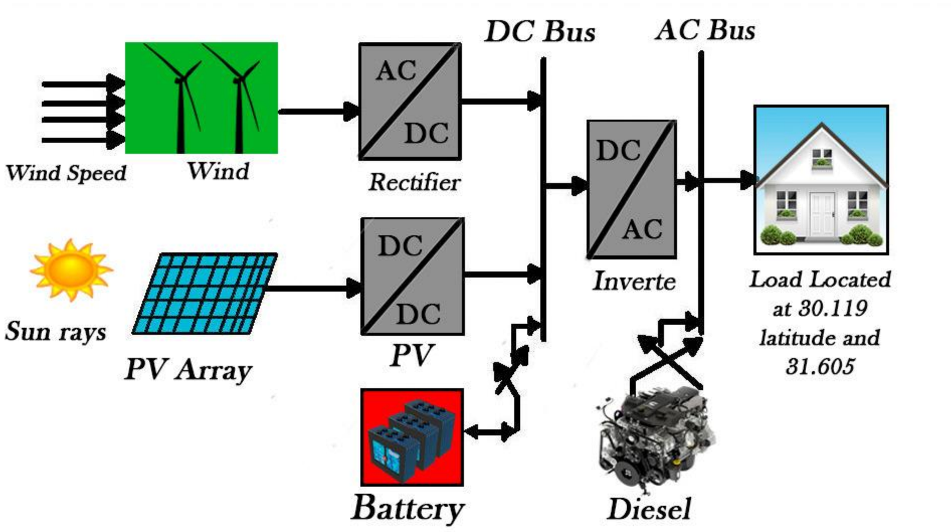

Figure 1. Schematic diagram for the proposed hybrid multi source MG system

2.1. WT modeling

WT uses kinetic energy from wind speed to produce mechanical energy and then this produced mechanical energy is utilized for generating the electrical energy (Govardhan & Roy, 2012). WT electrical energy is calculated for each time based on site weather and height of installation for WTs (Bansal, Kumar, & Gupta, 2013). The speed of wind, at a specific height, can be obtained from "NASA surface meteorology and solar energy". Modification of wind speed to the desired hub height, using the measured speed of wind at the reference height, is significantly required (Tito, Lie, & Anderson, 2015), (Hassan, El-Saadawi, Kandil, & Saeed, 2016).

The energy output from the WT, at a site wind speed, is obtained using the WT power curve that is denoted by manufacturer. For a given speed profile, the energy available from wind can be modeled using equation (1) (Yazdanpanah, 2014):

$$E_{WT} = T_{hr} \sum_{v_{min}}^{v_{max}} P_o . f(v, k, c) \tag{1}$$

Where E_{WT} represents the energy output from WT in kWh at a given location, T_{hr} represents the time (hours) used in the study, P_o represents the power output of WT (kW), (v_{min}, v_{max}) represents the minimum and maximum speeds of wind, and $f(v, k, c)$ represents the Weibull function for a given site wind speed (v) at a designed shaping coefficient k and scaling coefficient c.

The Energy Pattern Factor (EPF) approach is required and recommended for more precise determination of c and k coefficients. This is to reduce uncertainties concerning with the output wind energy calculation for Wind Energy Conversion System (WECS) (Kidmo, Danwe, Doka, & Djongyang, 2015).

2.2. PV modeling

PV modules are systems in which sunlight straight converted into electricity. The energy per year of a PV module, at a certain location with a known solar Irradiation and temperature, can be modeled using equation (2).

$$E_{PV} = T_{hr} \sum_{G_{min},T_{min}}^{G_{max},T_{max}} P(T, G) \tag{2}$$

Where E_{PV} is the energy production per year of PV module, T_{hr} represents time (hours) through which the sun hits the PV modules and $P(T, G)$ represents the PV modules output power at a solar irradiation G and temperature T of hourly average values, which is calculated using equation (3) (Mohamed & Koivo, 2011).

$$P_{PV}(T, G) = P_{STC} \frac{G_{ING}}{G_{STC}} \left(1 + k(T_c - T_r)\right) \tag{3}$$

Where $P_{PV}(T,G)$ represents the PV power at incident irradiance and temperature, P_{STC} represents the maximum power for the PV at STC, G_{ING} is the fallen irradiation, G_{STC} represents the irradiation at STC (1000W/m^2), k is the power temperature coefficient (0.5 %/c^o), T_c is the cell temperature, and T_r is the reference temperature.

2.3. DG modeling

The conventional roles for diesel generations have been the condition of peak shaving and stand-by power (Mohamed el al., 2011). In this paper, DGs are supposed for sharing the wind/PV generations for feeding the load demand. DGs powers are related to their Fuel Consumption (FC). This means that they are characterized by their efficiency and fuel consumption. The DGs operate between 80 and 100 percent of their nominal powers for obtaining higher efficiency use (Hassan, Saadawi, Kandil, & Saeed, 2015). The energy that can be generated by a DG is determined by using the following equation (4) (Bilal et al., 2012):

$$E_{DG}(t) = P_{DG}(t) . \eta_{DG} . T_{hr} \tag{4}$$

Where E_{DG} is the DG energy per year in KWh, P_{DG} is the DG rating power, η_{DG} is the DG efficiency, and T_{hr} represents its hours of operations.

The fuel consumption of a DG depends on both the load and the size of generator. Hourly fuel consumption is given by equation (5) (Hassan et al., 2016).

$$FC(t) = a.P_o(t) + b.P_n \tag{5}$$

Where, (a & b) represents the coefficients for the fuel consumption curve and (P_o & P_n) are power output and nominal rating of the DG. In this paper, a is taken to be 0.081451 L/kWh while b is taken to be 0.2461 L/kWh (Hassan et al., 2016).

The total CO_2 emission amount can be determined using the following equation (6) (Hassan et al., 2016):

$$Q_{co2} = FC\ .EF \tag{6}$$

Where Q_{CO2} is the total CO_2 emission amount in (kg), FC is the fuel consumption in (kWh) and EF represents the emission factor for the fuel used in kg/kWh. For the diesel fuel considered in this article, the default CO_2 emission factor is 0.705 kg/kWh (Hassan et al., 2016).

Usage of a DG is not in line with prevention of air-pollution and minimization of CO_2 emission. A gas micro-turbine will be more environmentally friendly solution but it is not practical to be used in our location and its cost is higher besides its complex design. A tax on CO_2 levels of emissions in any sector did not yet applied by whether industrial or energy production in the site of the proposed MG. However, the department of environment stated, depending on the Environmental Law4 of 1994, that there is a need to force such a tax for emissions per year of that pollutant and harmful gas. The department of environment enumerated these ratings according to European standards.

2.4. Battery modeling

Battery is defined as an electro-chemical device that stores the electrical energy from AC or DC units of MG for later use. Since the output of the renewable sources of the MG is a random behavior, the state of charge (SOC) of the battery is constantly changing accordingly in MG system. When the total power output from the WTS, PV modules is greater than the load power, the battery is in the SOC. When the total output power of the WT and PV modules is less than the load power, the battery is in the discharging state. The SOC of battery bank can be calculated from the following equation (7) (Wei, 2007):

$$SOC(t) = SOC(t-1).(1-\sigma) + \left[E_{Gt}(t) - \frac{E_L(t)}{\eta_{inv}}\right].\eta_{bat} \tag{7}$$

Where, $SOC(t)$ and $SOC(t-1)$ are the battery bank state of charge at time t and t-1, σ is monthly self-discharging rate, $E_{Gt}(t)$ is the total energy generated, $E_L(t)$ is the load demand, η_{inv} and η_{bat} are the efficiency of inverter and battery.

In this paper, the battery SOC model is designed based on the Ah method. The capacity of battery bank (B_{Req}) required for a MG system can be calculated using the following equation (8) (Hassan et al., 2016).

$$B_{Re\,q} = \frac{L_{Ah/day}.N_c}{M_{DD}.D_f} \tag{8}$$

Where $L_{Ah/d}$ is the total Ah consumption of the load per day, M_{DD} is the maximum discharge depth and D_F is the factor of discharging and N_C represents the autonomous day's number.

The number of parallel connected batteries (N_p) for giving the Ah needed by the MG system is determined using equation (9), while the number of series connected batteries (N_s) for giving the system voltage V_N is determined using equation (10) (Yazdanpanah, 2014).

$$N_p = \frac{B_{Re\,q}}{B_c} \tag{9}$$

$$N_s = \frac{V_N}{V_B} \tag{10}$$

Where B_{Req} is the required capacity of the battery bank in Ah, B_C is the the selected battery capacity, V_N is the MG system voltage and V_B is the battery voltage. The total batteries number N_{BT} is obtained as indicated by equation (11).

$$N_{BT} = N_p . N_s \tag{11}$$

2.5. PV controller modeling

The Maximum Power Point Tracker (MPPT) controller is implemented as a PV controller which tracks MPP of the PV system. This is achieved throughout the day delivering the maximum amount of the available solar energy to the MG system. MPPT controller comprises a number of PV controllers needed for the MG system. The PV controller numbers required for a PV system is calculated by using the equations 12, 13, and 14 (Hassan et al., 2016), (Hassan et al., 2015).

$$P_{pv\_Rtot} = N_{pv} . P_{pv\_R} \tag{12}$$

$$P_{max\_con} = V_b . I_{con} \tag{13}$$

$$N_{con} = \frac{P_{pv\_Rtot}}{P_{max\_con}} \tag{14}$$

Where I_{con} represents the maximum current which the controller handles from the PV to the battery, V_b is the voltage of the battery, P_{PV_R} is the PV rated power at STCs, P_{PV_Rtot} is the total power of the PVs at STCs, P_{max_con} represents the maximum power of one controller, and N_{PV} represents the total number of PV modules.

2.6. Inverter modeling

Inverters are generally used as the interface to connect energy between MG components and the load. The selected power inverter must be capable of handling the maximum power expected by AC loads (Bilal el al., 2012), (Hassan, El-saadawi, Kandil, & Saeed, 2015).

Inverters are classified into three main different schemes. These types are standalone, grid tied battery less and grid tied with battery back-up inverters (Hassan el al., 2015). In this paper, the stand alone inverter is used. The number of inverters needed for a certain load demand can be modeled and enumerated using equation (15) (Solar Energy International, (2007).

$$N_{inv} = \frac{P_{g\_max}}{P_{inv\_max}} \tag{15}$$

Where P_{inv_max} represents the maximum power that the inverter can supply, P_{g_max} is the maximum power that the MG system generates, and N_{inv} represents the inverter numbers.

3. Optimal design of MG configuration

The optimal design of MG configuration that can manage the load makes the best compromise between the MG system CO_2 emissions and the cost of energy to optimize the fitness function in the MG system lifetime.

3.1. Objective function

The objective of the proposed approach is the design of optimal MG configuration scheme that can manage the prescribed load under the suggested objective/fitness function and various constraints. The objective/fitness function in this paper is to minimize the system TIC through the system lifetime in the standalone mode. The unknown variables are the number of wind turbines, PV modules, batteries, controller units, inverter units, and diesel generators. These variables represent the number of equipment needed to supply the load at minimum investment cost with CO_2 constraints. The problem is solved for two scenarios: cost minimization without emissions constraints and cost minimization with emissions limitations. The mathematical model for the general objective/fitness function can be formulated as follows (Hassan et al., 2016):

$$TIC = \sum_{i=1}^{n_{WT}} N_{WTi} \,.\, C_{WTi} + \sum_{j=1}^{n_{PV}} N_{PVj} \,.\, C_{PVj} + \sum_{k=1}^{n_{BAT}} N_{BATk} \,.\, C_{BATk} + \sum_{l=1}^{n_{DG}} N_{DGl} \,.\, C_{DGl} + \sum_{m=1}^{n_{CON}} N_{CONm} \,.\, C_{CONm} + \sum_{y=1}^{n_{INV}} N_{INVy} \,.\, C_{INVy} \quad (16)$$

Where N_{WT}, N_{PV}, N_{DG}, N_{BAT}, N_{CON}, and N_{INV} are number for each type to be selected of WTs, PV modules, DGs, batteries, controllers and inverters. C_{WT}, C_{PV}, C_{DG}, C_{BAT}, C_{CON}, and C_{INV} are the total investment cost for each type of a WT, a PV, a DG, a battery, a controller, and an inverter.

The TIC of the DG comprises the capital (C_{cap}), the operating & maintenance per year ($C_{O\&M}$), the fuel (C_f) and the pollutant CO_2 emissions costs (C_{em}). The TIC for other MG components contains capital (C_{cap}), installation (C_{ins}), and operation & maintenance ($C_{O\&M}$) costs. The following equations (17 to 22) demonstrates the mathematical model used for calculating the TIC for DG, wind turbine, PV module, battery bank, a controller, and inverter, respectively (Bilal el al., 2012).

$$C_{DG} = (\frac{C_{Cap_{GD}}}{4} + C_{f_{DG}}.H_{Ann} + C_{O\&M\_WT}.H_{Ann} + C_{em}).T_{life\_Pr} \quad (17)$$

$$C_{WT} = C_{Cap\_WT} + C_{Ins\_WT} + T_{Lifetime}.C_{O\&M\_WT} \quad (18)$$

$$C_{PV} = C_{Cap\_PV} + C_{Ins\_PV} + T_{Lifetime}.C_{O\&M\_PV} \quad (19)$$

$$C_{Bat} = C_{Cap\_Bat} + C_{Ins\_Bat} + C_{Re\,p\_Bat}.N_{Re\,p\_Bat} \quad (20)$$

$$C_{Con} = C_{Cap\_Con} + C_{Ins\_Con} + T_{Lifetime}.C_{O\&M\_Con} + C_{Re\,p\_Con}.N_{Re\,p\_Con} \quad (21)$$

$$C_{Inv} = C_{Cap\_Inv} + C_{Ins\_Inv} + T_{Lifetime}.C_{O\&M\_Inv} + C_{Re\,p\_Inv}.N_{Re\,p\_Inv} \quad (22)$$

Where H_{ann} is the number of hours that the DG can be used in one year (6*365), $T_{lifetime}$ is the life time for the project (20 years) and N_{Rep} is the number of unit replacements through the lifetime period. In this paper, the lifetime of both PV modules and WT is supposed to be 20 year, the inverter and controller is life time is supposed to be 10 years, and the batteries life time is assumed to be 5 years (Bilal el al., 2012). The MG units replacement costs (C_{rep}) are considered to be the same as their capital costs.

3.2. Constraint for energy balance

The total generation of yearly energy (kWh/year) have to exceed or at least equal to the effective energy of the annual consumption. The effective energy of annual consumption is the energy consumed by the yearly load demand divided by the efficiency of the overall system (η_{sys}). The energy balance can be modeled using equation (23) and the overall system efficiency can be determined as equation (24) indicates (Hassan et al., 2016).

$$\sum_{i} N_{WT} . E_{WT} + \sum_{j} N_{PV} . E_{PV} + \sum_{l} N_{DG} . E_{DG} \geq \frac{E_{Load}}{\eta_{sys}} \tag{23}$$

$$\eta_{sys} = \eta_{DG} . \eta_{Bat} . \eta_{Con} . \eta_{Inv} . \eta_{W} \tag{24}$$

Where E_{load}, E_{WT}, E_{PV}, and E_{DG} represent the energy consumption of the load, generated by WTs, PV modules, DGs, in (kWh/year). η_{sys}, η_{Inv}, η_{Con}, η_{W}, η_{Bat}, and η_{DG} represent overall MG system, inverter, PV controller, connection wires, battery, and DG efficiencies. The average efficiency for DG, battery, PV controllers, inverter, and wires, are shown in Table 1.

Table 1. Efficiencies for components of MG.

MG components	**Efficiency**	**MG components**	**Efficiency**
DG	0.85	Inverter	0.95
battery	0.85	Wires	0.90
PV controller	0.95	–	–

3.3. Much bounds and size of design variables constraints

These constraints involve physical limits on the number of MG generation sources according to the available area of the land of the project. It also contains limits with respect to the sizing of the PV units as well as controllers and inverters and constraints to the *SOC* of batteries. These constraints can be modeled as indicated by the following equations (25 to 30):

$$0 \leq N_{WT} \leq N_{WT\_max} \tag{25}$$

$$0 \leq N_{PV} \leq N_{PV\_max} \tag{26}$$

$$0 \leq N_{DG} \leq N_{GD\_max} \tag{27}$$

$$\sum_{j} N_{Con} . P_{Con} \geq P_{PV\_max} \tag{28}$$

$$\sum_{i} N_{Inv} . P_{Inv} \geq P_{max} \tag{29}$$

$$SOC_{Min} \leq SOC \leq SOC_{Max} \tag{30}$$

Where $N_{WT\text{-}max}$, $N_{PV\text{-}max}$, and $N_{DG\text{-}max}$ represent the maximum number of WTs, PV modules and DG units. P_{IN}, P_{CON}, $P_{max,}$ and $P_{PV\text{-}max}$ represent the maximum output power of inverter, PV controller, load, PV module in watts and *SOC* is the battery state of charge.

3.4. Diesel operation constraints

DG should have operation time limits for reducing wear and tear. This limitation can be modelled using equation (31).

$$0 \leq \sum_{T=1}^{T=24} T_{DG} \leq T_{max} \tag{31}$$

Where T_{DG} represents the time in hours that the DG operates daily and T_{max} is the maximum permissible time that the DG operates per day.

3.5. CO2 emissions constraints

The CO_2 emissions amount in kg is an indication parameter for the environmental pollution. It represents the maximum percentage of the CO_2 emission results in fuel combustion. Up till now, there are no maximum governmental permissible limits or level of CO_2 emissions in country where of the MG project is proposed (Hassan et al., 2016). In this paper, a maximum permissible level of CO_2 (kg) is suggested for investigating the impact of CO_2 on the optimal MG system configuration and TIC. This limitation can be supposed according to equation (32).

$$CO_2 \leq CO_{2\_max} \quad (32)$$

Where CO_{2-max} represents the maximum permissible limit of the CO_2 harmful emissions in (kg).

4. Optimal MG configuration approach and case study

4.1. Optimal method

The MG configuration optimization problem is solved by using the MATLAB optimal search code. The GA and PSO techniques used by authors in (El-Wakeel, El-Eyoun, Ellissy, & Abdel-hamed, 2015) are implemented with the proposed modules of MATLAB code. This is achieved to determine the numbers of WTs, PVs, DG units, batteries, PV controllers, and inverters. This configuration supplies the load described in subsection 4.2.1 and reduces the TIC per year taking into accounts the pollutant CO_2 emission limits. The MATLAB code which is divided into four module codes as shown in Fig. 2 is designed to represent and execute the proposed approach.

The 1st module calculates the energy generated per year by any given type of WT based on the designed model illustrated in section 2.1. A combination of WTs power curve and Weibull is used by this module. The input information for that module are: the WTs power curves, the resource for wind speeds at both hub and tower height.

The energy generated annually by any given type of a PV array, based on the mathematical model explained in section 2.2, is calculated by using the 2nd module. The data entered for the module are: power rating of each WT type, the site temperature and irradiance levels.

The 3rd module computes the annual energy generated by any given type of DG based on the mathematical model explained in section 2.3. The data entered for the module are: the diesel generator rated power, the diesel generator efficiency, and its operation time.

The 4t h module is the GA, and PSO technique (El-Wakeel, El-Eyoun, Ellissy, & Abdel-hamed, 2015) used with the objective/fitness function for the optimization of the proposed configuration. All the previous results from first, second, and third modules are the inputs to fourth module besides the data for controllers, inverters, and batteries. This module calculates the optimal number of MG system components supplying and managing the specified load based on minimum TIC for all components with CO_2 emissions constraints considerations.

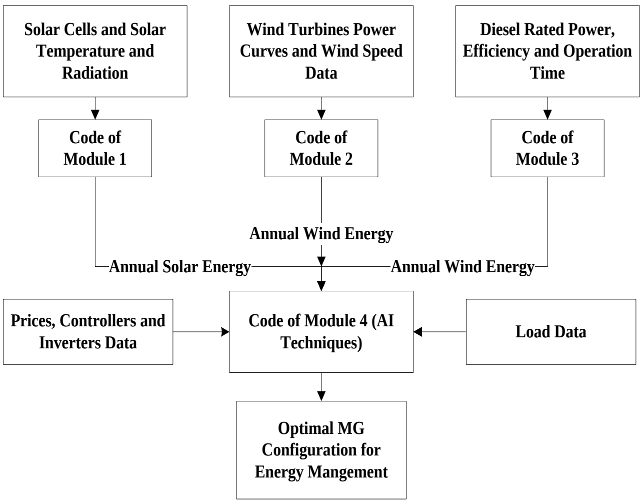

Figure 2. Modules of the suggested optimization scheme

A detailed computational procedure of fourth module, for optimal MG system configuration, is indicated by Fig. 3. The input data are 1) The data related to meteorological information of the selected location. This data is obtained from NASA. 2) The unit prices of the projected MG system components including installation, operation & maintenance costs, components life time which are acquired from (Hassan el al., 2015). 3) Other inputs are fitness function, constraints and load data explained previously.

The optimal composition of PVs, WTs, DGs, batteries, controllers, and inverters from different brands are calculated by using PSO and GA as follows:

- **Using GA**

The initial population of the chromosomes that represents the number of each component of the MG is randomly generated. The chromosomes are evaluated according to the selected fitness function described in Subsection 3.1. A new population based on the fitness of the individuals is selected from the old one. Genetic operators (mutation and crossover) are applied to members of the population to create new solutions. The process of evaluation and new population creation is continued until a satisfactory solution based on specific termination criteria has been satisfied. Usually the maximum number of generations is used as the termination criterion. Experience shows that mutation should be done with a low probability ranging from 0.1 to 2%, while the crossover rate should be between 60 to 90%. Again, the GA has been run for 20 independent trials with different settings until the solutions are very close to each other. According to the trials, GA parameters are determined as: maximum number of iterations/generations =100, population size = 3000, the cross over rate = 0.9 and the mutation rate = 0.001.

- **Using PSO**

In the PSO algorithm, a population of particles is put into the dimensional search space with randomly chosen velocities and positions knowing their best values so far (*pbest*) and the position in the d-dimensional space. The velocity of each particle is adjusted according to its own flying experience and the other particles' flying experience. The fitness function value is calculated for each particle. If the value is better than the current *pbest* of the particle, the *pbest* value is replaced by the current value. If the best value of *pbest* is better than the current *gbest*, the *gbes*t is replaced by the best value and the particle number with the best value is stored. The operation is continued until the current iteration number reaches the predetermined maximum iteration number. The PSO algorithm has been run for 20 independent trials with different settings until the solutions are very close to each other. According to the trials, the PSO parameters are determined as: maximum of iterations/generations=100, number of particles/agents = 3000, acceleration constant c_1= 0.6, c_2 = 1.4 and weighting factor = 0.95.

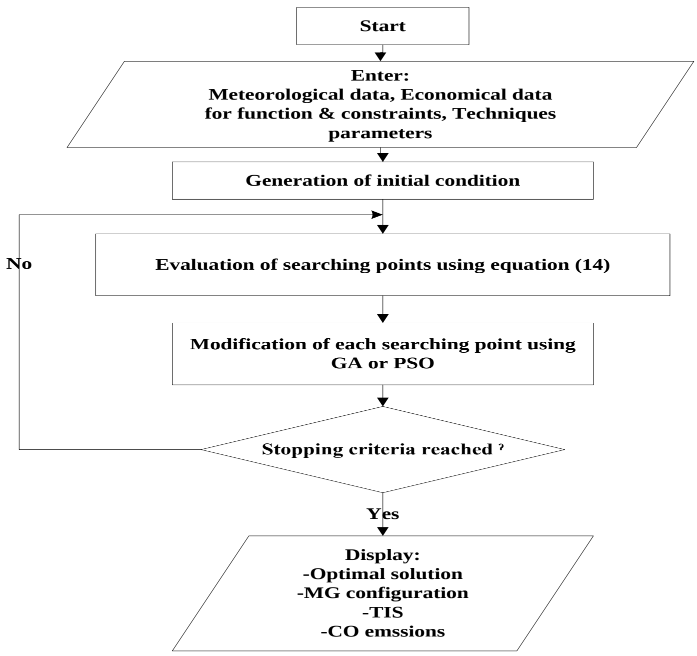

Figure 3. Computational procedure flow chart using PSO or GA

4.2. Case study

The case study is a typical isolated MG suggested to supply a load located between (30.119 latitude and 31.605 longitude). It consists of different types of energy generation units such as WTs, PVs, DGs, and battery banks as a storage system. The optimization scheme is used to find the optimal configuration and energy management of the MG components that satisfy the objective/fitness function discussed previously in equation (16). Input data includes the load data, meteorological data of the suggested location, and techno-economical data of the MG system components.

4.2.1. Load data

It is considered that outdoor and indoor lighting load for educational building located between (30.119° latitudes and 31.605° longitudes) will be met by a MG system. Table 2 shows the daily electrical load requirements, with a load of 50 kW peak. Using Table 2 and actual load measuring, a load profile is built as indicated by Fig. 4. It shows the daily load profile for proposed MG system with a maximum value of 50 kW and an average consumption per day of 516.724 kWh.

Table 2. Daily electrical load requirements

Purpose	**entrance**	**outdoor**	**Indoor**
Rated power (kW)	1.08	14.588	49.968
Operation period (h)	6	11	7
Dailyenergy(kWh/day)	6.48	160.468	349.776
Total daily energy (kWh/day)	516.724		

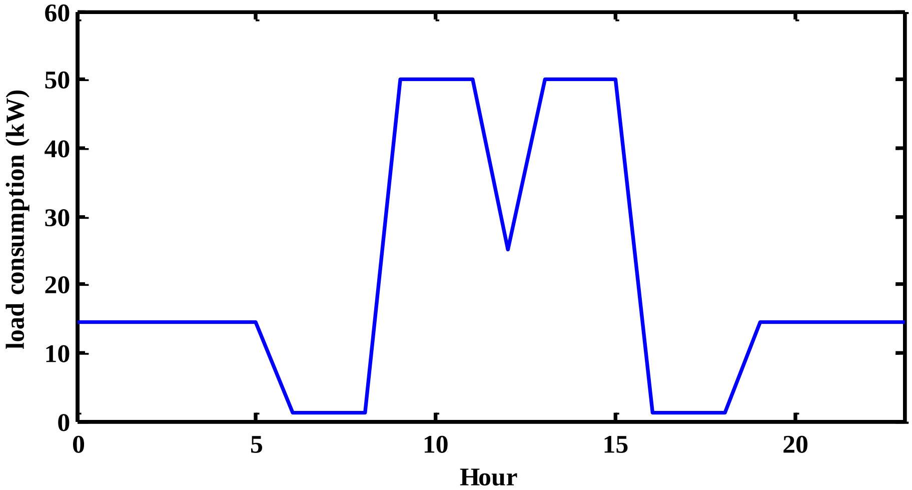

Figure 4. Considered daily load profile

4.2.2. Meteorological and techno-economical data

The solar radiation and wind speed are obtained from "NASA surface meteorology and solar energy". The monthly average insulations and air temperature (°C), for the suggested location, incident on a horizontal surface are indicated by Table 3 and Table 4 respectively. Whereas, the average values per month of the wind speed at (50 m) above the earth surface are indicated by Table 5. As explained before in Section 2.1, it is found necessary to adjust the wind speed to the hub height if the speed is measured at a height different than that of turbine hub height. In this paper the wind towers are taken with a 20 meters height, so that the measured wind speed values have to be modified as it is obvious in Table 6. The techno-economic data of the used commercial components in this article are taken as in (Hassan el al., 2015) (21 types of WTs, 13 types of PVs, 1 types of DGs, 5 types of PV controllers, 5 types of inverters, 20 types of batteries).

Table 3. Monthly averaged isolation for the suggested location

Month	Jan	Feb	Mar	Apr	May	Jun	Annual average
22-years average solar radiation (kWh/m2/day)	3.23	3.91	5.11	6.28	6.99	7.69	5.35
Month	Jul	Aug	Sep	Oct	Nov	Dec	
22-years average solar radiation (kWh/m2/day)	7.33	6.85	5.86	4.48	3.45	3.00	

Table 4. Averaged air temperature/month for the suggested location

Month	Jan.	Feb	Mar	Apr	May	Jun	Annual average
22-years average air temperature (°C)	13.3	13.6	16.0	20.1	23.4	26.3	21
Month	Jul	Aug	Sep	Oct	Nov	Dec	
22-years average air temperature (°C)	28.2	28.2	26.3	22.8	18.9	14.8	

Table 5. Averaged wind speed/month at 50 m from the surface for for the suggested location

Month	Jan	Feb	Mar	Apr	May	Jun	Annual average
measured wind speed at 50 m height (m/s)	4.74	5.01	4.99	4.78	4.80	4.68	4.75
Month	Jul	Aug	Sep	Oct	Nov	Dec	
measured wind speed at 50 m height (m/s)	4.73	4.71	4.78	4.68	4.44	4.71	

Table 6. Averaged modified wind speed/month for the suggested location

Month	Jan	Feb	Mar	Apr	May	Jun	Annual average
Modified speed at 20m height(m/s)	4.1584	4.3953	4.3778	4.1935	4.2111	4.1058	4.1709
Month	Jul	Aug	Sep	Oct	Nov	Dec	
modified speed at 20 m height (m/s)	4.1497	4.1321	4.1935	4.1058	3.8952	4.1321	

5. Optimization results and analysis

The optimum MG system configuration, that meets the energy required by the previously mentioned load profile with minimum TIC and emissions limits, is obtained by performing the designed optimization scheme explained in subsection 4.1. Table 7 indicates the bounds and size of design variables Constraints used in this paper. The simulation results to obtain minimum TIC without and with various emission limits using GA, and PSO techniques are explained in the following subsections.

Table 7. Indicates the bounds and size of design variables Constraints

Optimal Search limits	N_{WT}	NPV	N_{DG}	N_{Bat}	N_{CON}	N_{INV}	T_{DG} (hours)
Minimum (lower Limit)	0	0	0	0	0	0	0
Maximum (upper Limit)	1	40	20	10	50	10	6

5.1. Using PSO without CO2 emissions constraint

In this configuration, Table 8 indicates different types and numbers of wind turbines, PV modules, diesel generators, inverters and controller in the designed MG configuration indicated in Fig. 2 and explained in details previously in subsection 4.1. Number of different battery types is also used for charging the excessive energy in case of generation higher than load and to supply the load in case of generation is higher. In this case, per year total generated energy is of 321650.34 kWh, and per year consumption of energy is 321603.88 kWh. The model represents a MG system configuration with a TIC value of $47822.59 with emissions of 15146.06 kg of CO_2.

Table 8. MG sizing optimization results without emission constraint

MG	Commercial type	Rated cap.	No.	Commercial type	Rated cap.	No.
Wind	SouthWest (Air X)	400W	1	Bornay-Inclin 6000	6000W	1
	SW(Whisper 500)	3000W	1	ARE110	2500W	1
	AE (Lakota)	800W	1	ARE442	10000W	1
	Bergey (BWC 1500)	1500W	1	Kestrel Wind (800)	800W	1
	Bergey(BWCExcelR)	8100W	1	KestrelWind(3000)	3000W	1
	Bornay (Inclin 600)	600W	1	Solacity (Eoltec)	6000W	1
	Bornay (Inclin 1500)	1500W	1	–	–	–
PV	Sharp ND-250QCS	250W	32	CSI CS6X-285P	285W	39
	Hyundai HiS-255MG	255W	36	CanadianSolar250P	250W	33
	Lightway	235W	40	CSI CS 6X-295P	295W	40
	Trina TSM-PA05	240W	40	CanadianSolar300P	300W	40
	SolartechSPM135P	135W	16	CanadianSolr255M	255W	37
	CSI CS6P-235PX	235W	21	HyundaiHiS260MG	260W	37
	CSI CS6X-280P	280W	40	–	–	–
DG	STEPHIL -SE 3000D	1900W	11	–	–	–
Battery	MK8L16	370Ah	1	US Battery US2200	225Ah	2
	Surrette2Ks33Ps	1765A	8	US Battery US250	250Ah	1
	SurretteS1-460	350Ah	1	SurretteS2-460	350Ah	1
	Trogan T-105	225Ah	2	SurretteS530-6v	400Ah	2
	US Battery US185	195Ah	1	–	–	–
Controller	SE-XW-MPPT-60	1500W	30	Outback FM60	1500W	12
	Outback FM80	2000W	27	Blue Sky SB3048	750W	8
Inverter	SE-XW6048	6000W	4	FX-2024ET	2000W	2
	SE-XW4548	4500W	2	SE-XW4024	4000W	4
TIC ($)		47822.5970				
CO_2 (kg)		15146.06				

5.2. Using PSO with CO2 emissions constraint

For investigating the CO_2 emissions effect on the TIC of the MG system, a predetermined maximum permitted CO_2 emissions limits introduced. For CO_2 emissions constraints limited to 6884 kg, Table 9 presents the optimization results using PSO.

Table 9. MG sizing optimization results with emission constraint

MG	Commercial type	Rated cap.	No.	Commercial type	Rated cap.	No.
Wind	SouthWest (Air X)	400W	1	BornayInclin 3000	3000W	1
	SW (Whisper 200)	1000W	1	BornayInclin 6000	6000W	1
	SW(Whisper 500)	3000W	1	ARE110	2500W	
	SW(Skystream 3.7)	1800W	1	ARE442	10000W	1
	Bergey-BWCExcelR	8100W	1	Kestrel Wind (1000)	1000W	1
	Bornay (Inclin 250)	250W	1	Kestrel Wind (3000)	3000W	1
	Bornay (Inclin 1500)	1500W	1	Solacity (Eoltec)	6000W	1
PV	Sharp ND-250QCS	250W	40	CSI CS6X-285P	285W	40
	HyundaiHiS-255MG	255W	40	CanadianSolar250P	250W	40
	Lightway	235W	40	CSI CS 6X-295P	295W	40
	Trina TSM-PA05	240W	29	CanadianSolar300P	300W	39
	SolartechSPM135P	135W	21	CanadianSolr255M	255W	40
	CSI CS6P-235PX	235W	40	HyundaiHiS260MG	260W	40
	CSI CS6X-280P	280W	40	–	–	–
DG	STEPHIL-SE 3000D	1900W	5	–	–	–
Battery	MK8L16	370Ah	2	US Battery US185	195Ah	4
	Surrette2Ks33Ps	1765Ah	5	US Battery US2200	225Ah	3
	Surrette 4-Cs-17Ps	546Ah	4	US Battery US250	250Ah	3
	Surrette6-CS-17Ps	546Ah	2	SurretteS2-460	350Ah	2
	Trogan T-105	225Ah	4	SurretteS530-6v	400Ah	5
Controller	SE-XW-MPPT-60	1500W	17	SE-XW-MPPT-80	2000W	15
	Outback FM80	2000W	23	Blue Sky SB3048	750W	13
	Outback FM60	1500W	14	–	–	–
Inverter	SE-DR1524E	1500W	3	FX-2024ET	2000W	5
	SE-XW6048	6000W	4	SE-XW4024	4000W	4
	SE-XW4548	4500W	2	–	–	–
TIC ($)		48503.4315				
CO_2 (kg)		6884.5772				

It can be concluded from Table 9 that by decreasing the maximum allowable CO_2 emissions limits, number of DGs is decreased and consequently the number of PV modules, PV controllers, and WTs are increased. This will increase the installation cost of the MG system and therefore the TIC value will be increased to 48503.43$ instead of 47822.59$ without constraints.

5.3. Impact of CO2 emissions constraint with comparison between PSO and GA

In this section, comparison of impacts of CO_2 emissions constraint using PSO and GA is made. Table 10 indicates the CO_2 emissions constraints impacts on the MG configurations and also shows a comparison between the results of GA and PSO techniques. Figs 5 -7 show a comparison between energy generated with and without CO_2 emissions constraint.

Table 10. Impact of CO2 emissions constraints.

Item	**No CO_2 constraints**		**Maximum allowable CO_2 emissions 6884.5772 kg**	
Used Technique	**PSO**	**GA**	**PSO**	**GA**
Energy required by the load	321603.88	321603.88	321603.88	321603.88
Generated energy(kWh/year)	321650.34	321605.22	321776.51	321907.14
Surplus energy (kWh/year)	46.4619	1.3403	172.6333	303.25
Wind energy (kWh/year)	66557.88	46680.87	71602.43	71075.39
PV energy (kWh/year)	216187.10	236019.00	232489.83	233147.50
Diesel gen.Energy(kWh/year)	38905.35	38905.35	17684.25	17684.25
No. of DG	11	11	5	5
TIC ($/year)	47822.59	48553.92	48503.43	48688.70
% increase in TIC	base	base	1.42366	1.8110
Annual energy cost($/kWh)	0.14870	0.15097	0.15081	0.15139
CO_2_emissions(kg/year)	15146.06	15146.06	6884.57	6884.57
%CO_2 emissions decrease	base	base	54.5454	54.5454
Seeking Time (Sec)	55.2	88.5	57.6	90.7

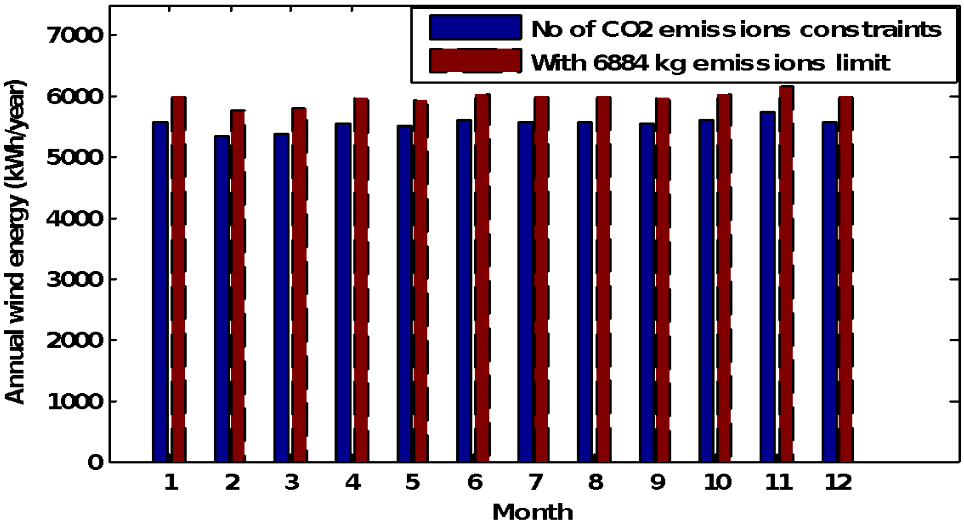

Figure 5. Monthly wind energy in a year with and without constraints using PSO

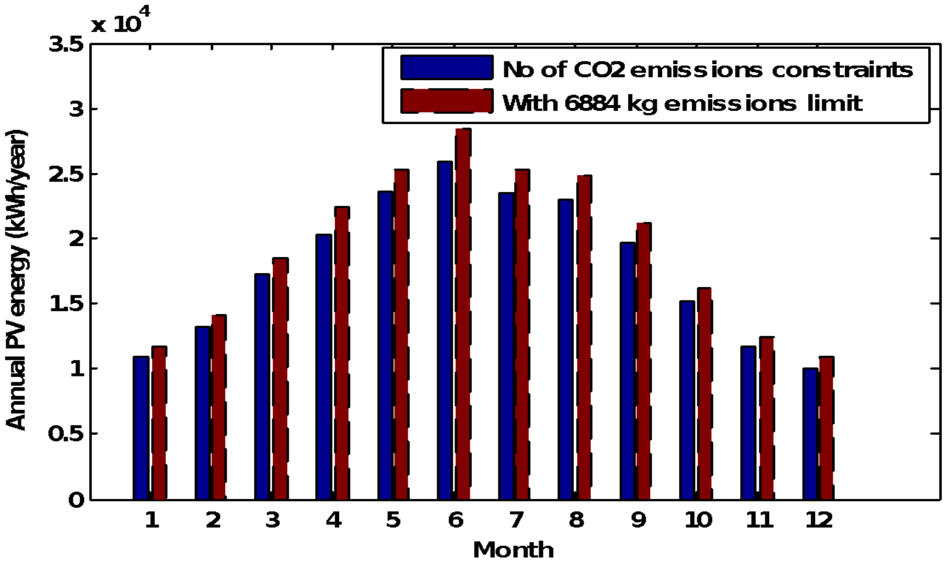

Figure 6. Monthly PV energy in a year with and without constraints using PSO

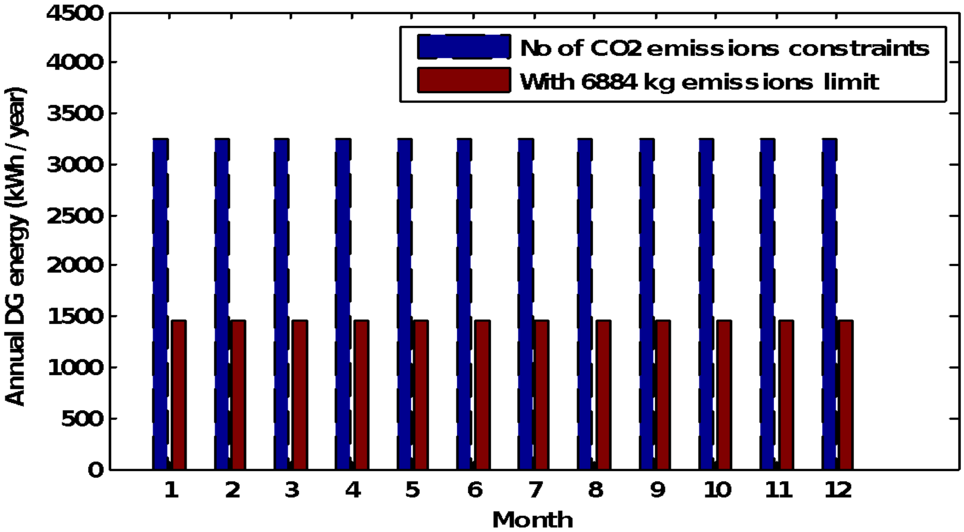

Figure 7. Monthly DG energy in a year with and without constraints using PSO

It can be concluded from Table 10 and Figs 5 -7 that by decreasing the maximum allowable CO_2 emissions limits, the number of diesel generators is decreased. Consequently, the designed scheme tends to select higher number of PV modules and WTs to overcome the decreasing in energy generated from diesel. This increase in WTs, PV units and PV controller will increase the TIC (1.4236% in PSO which is approximately zero) due to the increase of the installation cost of the system, but the CO_2 emissions is decreased to the required level (45.4545 %). It is obvious from Table 9 that the results obtained by the configuration scheme optimized by PSO is better than those obtained by GA. This is with respect to TIC emissions and annual cost of energy. Fig. 6 shows that the components of MG share higher power in April to August as the radiations of the selected site is higher at these months.

5.4. MG energy management

While designing and simulating the proposed MG, it was assumed that the MG is isolated and supplies the rated energy to the load throughout the project lifecycle. From Table 9, it is obvious that MG system configuration with a TIC of $48503.43 and 54.5454 % decrease in CO_2 emissions represents the most economical design with lower emissions. Thus this configuration is used for MG management and supplying the annual average load described in subsection 4.2.1.

Fig. 8 shows share of designed individual MG components (wind, PV, and diesel) in supplying the demand electricity for the load profile, whereas Fig. 9 indicates the monthly sharing of combined components and Fig. 10 shows the charged and discharged energy in batteries over the 12 month of the year.

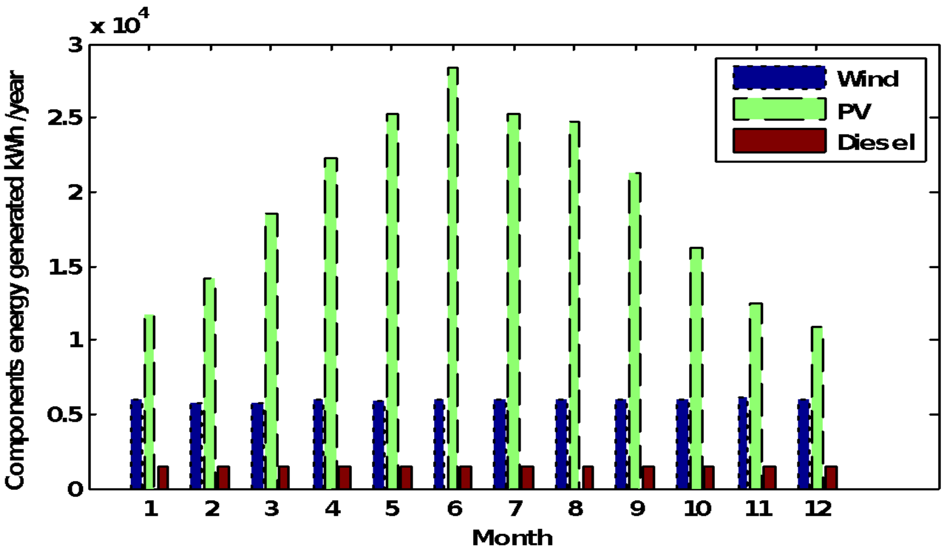

Figure 8. Load profile sharing using MG components with 6884 kg emissions constraints

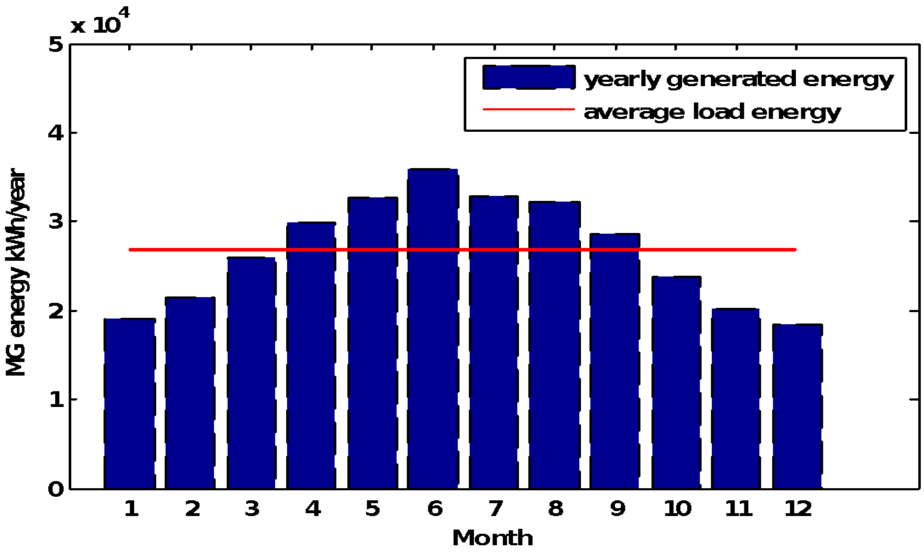

Figure 9. Grouped load profile sharing with 6884 kg emissions constraints

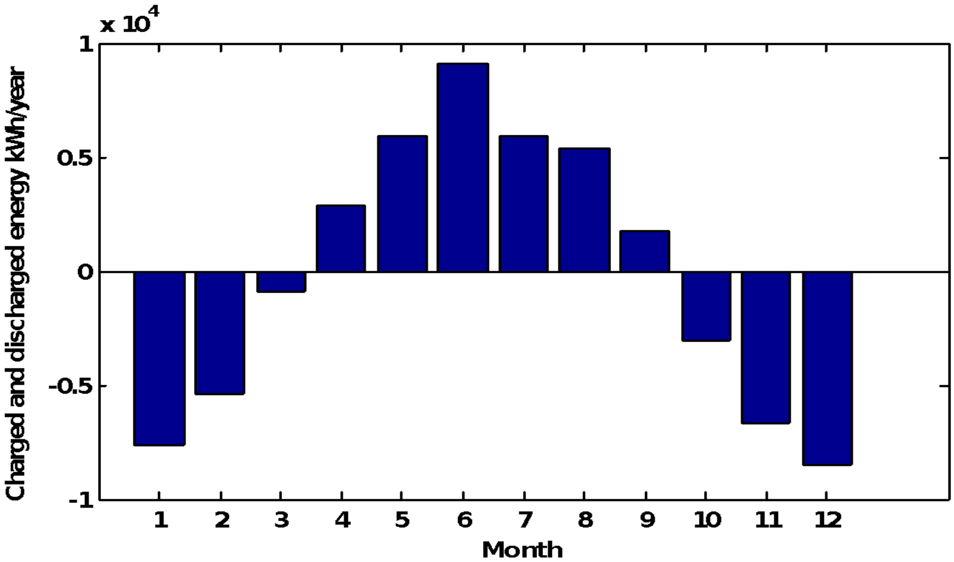

Figure 10. Surplus energy lost in batteries with 6884 kg emissions constraints

It is evident from Figs 8 -10 that with CO_2 emissions limitation, the DGs share the smallest part of the load profile energy. Also WTs shares poor energy due to the low wind speed profile of the MG site. The components of the MG share higher energy in April to August as the irradiations and temperature of the selected site are higher at these months. Results also proved that PV technology is preferable in this location.

6. Conclusion

In this paper, an optimal sizing scheme and energy management of MG components, supplying a load demand, is constructed and designed. The objective of minimizing the TIC with environmental emissions constraints is achieved. Limitations are also added to the optimization problem to take into accounts some of additional considerations found in an isolated MG system. Final results proved that the proposed optimization scheme is efficient and robust. Also the configuration scheme optimized with the help of PSO is better than those optimized using GA with respect to TIC, emissions and annual cost of energy. Finally, adding extra limits on CO_2 emissions constraints result in extra emissions reduction of 54.54% and negligible cost increase of 1.43% which emphasizes that the MG is designed economically with low environmental impacts. The meta-heuristic random search and optimization techniques are now emerging as a viable planning tools in smart grid optimization and renewable energy applications.

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