Optimal Configuration and Energy Management Scheme of an Isolated Micro-Grid using Cuckoo Search Optimization Algorithm

Abstract - This paper proposes an optimization scheme for optimal configuration and energy management of the micro-grid (MG), using the cuckoo search optimization algorithm (CSOA). The selected MG supplies a load profile located between 30.119 latitude and 31.605 longitude. The energy produced by the MG generation sources, according to meteorological data of the proposed location, is calculated using MATLAB. The objective/fitness function is modeled and designed for minimizing the total investment cost (TIC) including capital, investment, operation and maintenance costs. A novel weighted goal attainment function (WGAF) has been proposed to reduce CO_2 emissions and their associated costs. Moreover, WGAF also applies higher taxes on the amount of emissions that exceed governmental approved limits. To investigate the effects of WGAF on the TIC ($/year), annual cost of energy ($/kWh), and CO_2 emissions, various weighted coefficients are analyzed. The simulation results have shown that the designed optimization scheme can robustly and efficiently produce the optimal MG configuration that is both eco-friendly and generates economic benefits.

***Index Terms*–** Micro-grid (MG) optimization, energy management, cuckoo search optimization algorithm (CSOA), weighted goal attainment function (WGAF).

1. INTRODUCTION

A micro-grid (MG) is a local energy provider that reduces the energy expense and gas emissions by using distributed energy resources (DERs). MGs are treated as promising choices or even alternatives to existing centralized or traditional grids [1]. MGs employ a diversity of distributed generation (DG) units including photovoltaic (PV) cells, wind turbines (WT), and energy storage (ES) devices, such as batteries [2]. It is known that a very large number of population in the developing regions currently lacks grid based electric power services. In many cases, grid extension is not practically feasible. Therefore, MGs can play a pivotal role in reducing the electricity gap in various parts of developing world [1].

The proper selection and optimal sizing of DERs for a specific goal or objective are challenging and very important tasks in the design process of isolated MGs. The constrained optimization of a MG configuration is a challenging task, which can be accomplished by choosing a suitable non-linear programing technique [3].

In literature, several analytical and heuristic optimization techniques have been implemented on MG systems, cf. [4-9]. Rui Huang, et al., [10] proposed an approach for finding the optimal placements and sizes of MG components. The authors used genetic algorithm (GA), which is one of the heuristic-based evolutionary optimization methodologies for solving their proposed optimization problem. Behrooz Vahidi, et al., [11] proposed a model for optimal operation of a MG. The solution of their proposed optimization problem yielded a diversity of DG units usually used in MGs. The constraints considered in the proposed optimization problem reflect several limitations found in MG systems. The environmental costs had also been considered in the optimization problem. The problem was solved using bacterial foraging optimization algorithm (BFOA). Heikki N. Koivo, et al., [12] 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, operation, and maintenance.

A flexible generalized approach or methodology is essential for any kind of MG design for higher computational efficiency. Artificial intelligence (AI) techniques (that use bio-inspired technologies) are widely used, especially for complex large-scale optimization problems with linear and non-linear constraints. These techniques effectively increase the MG system efficiency by finding the best configuration to optimize the economic and technical criteria. Ramin Rajabioun in [13] proposed a new optimization algorithm which was inspired by the lifestyle of a bird called Cuckoo. The proposed algorithm is suitable for non-linear optimization problems. The algorithm was tested on 5 benchmark objective functions. The Cuckoo Search Optimization Algorithm (CSOA) was compared with the standard version of GA and particle swarm optimization (PSO) algorithms. The comparison showed the superiority of CSOA in fast convergence and global optima achievement. The results showed that CSOA has converged faster in less iterations. CSOA had found acceptable and very good determination of global minimum in small number of iterations.

This paper presents construction and design of an optimal configuration and energy management scheme of the MG components. An algorithm is designed for calculating the energy available from MG generation sources according to the meteorological data of the suggested location. The MG components are selected and designed to supply the suggested load to minimize the total investment cost (TIC). A novel WGAF is designed for limiting the CO_2 emissions and also to take into account the cost of the environmental emissions. The optimization problem is solved using CSOA. The results obtained via CSOA are also compared with those obtained from BFOA. Various weighting coefficients are selected to investigate the WGAF effects on the TIC in \$/year, annual cost of energy in \$/kWh, and CO_2 emissions. The proposed optimization scheme, used with CSOA, has the advantages that it is simple and can be extended to deal with more multi-objective functions besides dealing with more renewable and storage components for the MG. Also, 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.

This paper is organized as follows: description and modeling of the MG system components is introduced in Section 2; the steps involved in CSOA are explained in Section 3; the optimization problem for MG configuration is explained in Section 4; Section 5 describes the case study and implementation of the optimization scheme; simulation results are discussed in Section 6 and finally, the conclusions are provided in Section 7.

2. MODELING OF THE COMPLETE SYSTEM

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

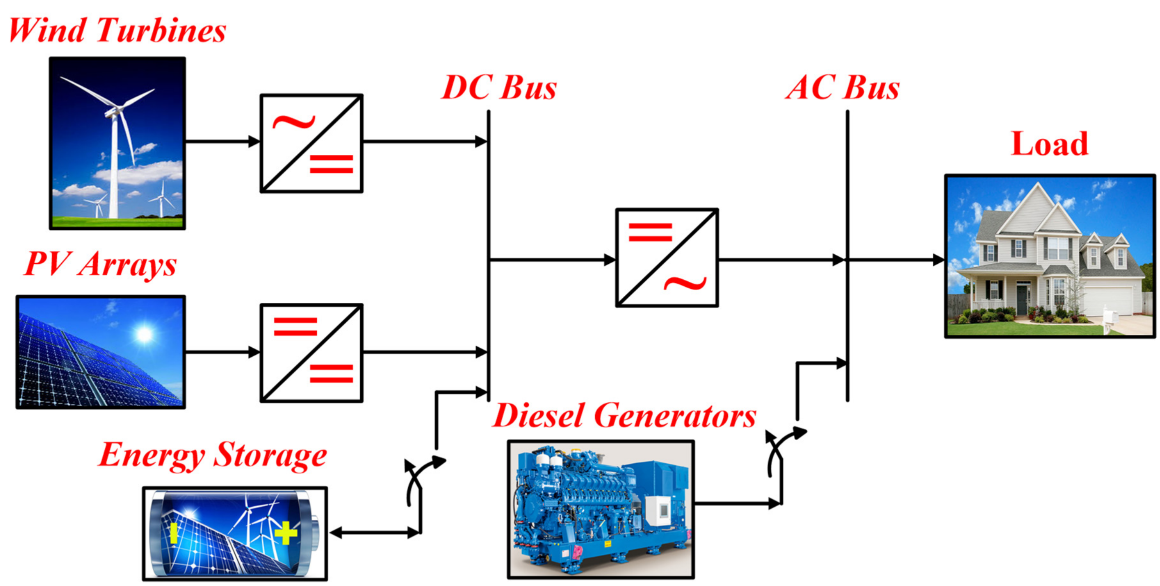

Fig. 1: Schematic diagram of the proposed MG system

2.1. WIND TURBINE MODELING

Wind Turbines (WTs) use kinetic energy (from wind speed) for producing mechanical energy that is then utilized for generating electrical energy [14]. The electrical energy generated by a WT can be calculated using its height and site weather information [15]. The speed of wind, at a specific height, can be sourced from "NASA surface meteorology and solar energy" [16]. The modification in speed of wind to the desired hub height, using the measured speed of wind at the reference height, is significantly required [17, 18]. The energy output from the WT, at a site wind speed, is obtained using the WT power curve denoted by the manufacturer. For a known or given speed profile, the energy available from wind can be modeled using [19]

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

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}) represent 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 the coefficients c and k. The use of EPE approach reduces the uncertainties concerning the output wind energy calculation for wind energy conversion system (WECS) [20, 21].

2.2. PV MODELING

Photovoltaic modules are systems in which straight sunlight is converted to electricity. The energy per year of a PV module at a certain location with a known solar irradiation and temperature can be modeled and calculated using

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

where E_{PV} is the energy production per year of PV, T_{hr} represents the time (hours) through which the sun hits the PV and $P(T, G)$ represents the PV output power in watts at a solar irradiation G and temperature T of hourly average values. The output power is calculated as [22, 23]

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

where 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 of power (0.5 %/c^o), T_c is the cell temperature and T_r is the reference temperature.

2.3. DIESEL GENERATOR (DG) MODELING

Traditional diesel generators have been the provider of peak shaving and stand-by power [22]. The power generated by DGs is characterized by their fuel efficiency and consumption. DGs operate between 80 and 100 percent of their nominal power for higher efficiency use [24]. The energy that can be generated by a DG is determined using [25]

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

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 hours of operation for DG.

Specific fuel consumption (SFC) (l/kWh) is "the fuel consumption needed to produce 1 kWh of energy and it is equal to hourly fuel consumption (l/h) to supply a given load during 1h". The fuel consumption of a DG depends on both the load and the generator size. The hourly fuel consumption and fuel cost of the DG are computed as

$$q(t) = aP_n(t) + bP_n, \tag{5}$$

$$C_{f_{DG}} = C_f(aP_n + bP_o), \tag{6}$$

where C_f is the fuel price in ($/L) including fuel transportation, a and b are the coefficients of fuel consumption curve, and P_o and P_n are power output and nominal capacity of the diesel generator, respectively. In this paper, a and b are taken as 0.081451 and 0.2461 L/kWh, respectively, [24] and C_f equals $0.4/L [26].

The total CO_2 emission amount can be determined using the following [17]

$$Q_{CO_2} = F_C\, E_f, \tag{7}$$

where Q_{CO_2} is the total CO_2 emission amount in (kg), F_C is the consumption of fuel in (kWh) and E_f represents the emission factor for the fuel used in (kg/kWh). For the diesel fuel considered in this paper, the default CO_2 emission factor is 0.705 kg/kWh [18].

The department of Environment, according to European standards [26], recommends a tax on the annual emissions of harmful CO_2 gas. Therefore, a novel weighted goal attainment function (WGAF) is designed and proposed in this paper to apply such a tax and limit the CO_2 emissions

$$C_{em} = C_1 c_3 Q_{CO_2} + C_2 c_4 Q_{CO_2}, \tag{8}$$

where C_{em} is the CO_2 emissions cost, C_1 and C_2 are weighted coefficients that reflect the values recommended by environmental Laws, c_3 and c_4 are selected such that $c_3 + c_4 = 1$ and $C_1 + C_2 \geq 0$.

2.4. BATTERY BANK MODELING

A battery is an electro-chemical device that stores electrical energy from AC or DC units of MG for later use. Since the output of the renewable sources (WT and the PV) of the MG is a random behavior, the state of charge (SOC) of the battery is constantly changing accordingly in a MG system [27]. The required capacity of a battery bank for a MG system can be determined as

$$B_{Req} = \frac{L_{Ah/day} N_c}{M_{DD} D_f}, \tag{9}$$

where B_{Req} is the required capacity of the battery bank in Ampere-hour (Ah), $L_{Ah/day}$ is the Ah consumption of the load per day, M_{DD} is the maximum discharge depth, D_f is the discharging factor and N_c represents the autonomous day's number.

The number of parallel connected (N_P) batteries for giving the Ah needed by the MG system is determined using Eq. (10), while the number of series connected (N_s) batteries for the given V_N is determined using Eq. (11) [18].

$$N_P = \frac{B_{Req}}{B_c}, \tag{10}$$

$$N_s = \frac{V_N}{V_B}, \tag{11}$$

where B_c is the selected battery capacity in Ah, V_N is the MG system voltage and V_B is the voltage of battery.

The total number of batteries (N_{BT}) is calculated as

$$N_{BT} = N_P N_s. \tag{12}$$

2.5. PV CONTROLLER MODELING

The maximum power point tracking (MPPT) controller is implemented as a PV controller that tracks MPP of the PV module. This is achieved throughout the day delivering the maximum amount of the available solar energy to the MG system [28]. The MPPT controller sizing consists of determining the number of PV controllers needed for the MG system. It is calculated using Eq. (13), (14), and (15) [18, 24]

$$P_{PV\_R_{tot}} = N_{PV} P_{PV\_R}, \tag{13}$$

$$P_{\max\_con} = V_b I_{con}, \tag{14}$$

$$N_{con} = \frac{P_{PV\_R_{tot}}}{P_{\max\_con}}, \tag{15}$$

where I_{con} represents the maximum current which the controller handles from the PV cell to the battery, V_b is the voltage of the battery, P_{PV_R} is the PV rated power at *STCs*, $P_{PV\_R_{tot}}$ 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 used inverter must be capable of handling the maximum energy predictable by AC loads [25, 29]. The inverters are classified into three main schemes: stand-alone, grid-tied battery-less, and grid-tied with battery backup inverters [24, 30]. In this paper, the stand-alone inverter is used. The number of inverters needed for a certain load demand can be modeled and enumerated as [31]

$$N_{inv} = \frac{P_{g\_max}}{P_{inv\_max}}, \tag{16}$$

where P_{inv_max} represents the maximum power that the inverter can supply, P_{g_max} is the maximum power that the MG generates, and N_{inv} represents the number of inverters.

3. CUCKOO SEARCH OPTIMIZATION ALGORITHM (CSOA)

Cuckoo Search Optimization Algorithm (CSOA) is “a meta-heuristic algorithm inspired by the obligate brood parasitism behavior of some species of a bird family called Cuckoo” [32]. These types of Cuckoo birds lay their eggs in the nests of the other host birds with fantastic abilities such as selecting the nests that are recently produced and removing existing eggs to increase the probability of their eggs hatching. The host bird takes care of the eggs presuming that the eggs are its own. However, some of host birds can identify their own egg from imposter's cuckoo eggs. These birds will either build new nests in other locations or throw out the discovered alien eggs. The cuckoo breeding analogy is used for developing optimization algorithm. The CSOA method and the steps to search the optimum solution are given in the following sub-sections. Prior to the implementation of CSOA, some parameters need to be initialized, which include number of nests (*n*), discovering probability (*pa*), the step size parameter (α) and the maximum number of generation as termination criteria.

3.1. GENERATION OF INITIAL NESTS OR EGGS OF HOST BIRDS

The initial locations of the nests are determined by the set of random values specified to each variable as indicated by

$$nest_{i,k}^{o} = round(x_{k,min} + rand\ (x_{k,max} - x_{k,min})), \tag{17}$$

where $nest_{i,k}^{o}$ represents the initial value of the k^{th} variable for the i^{th} nest, $(x_{k,max}, x_{k,min})$ are the minimum and the maximum allowable values for the k^{th} variable and $rand$ is a random number in the interval [0, 1]. The $round$ function is used due to the discrete nature of the optimization problem.

3.2. GENERATION OF NEW CUCKOOS BY LEVY FLIGHTS

Except for the best one, all the nests are displaced according to the quality of new cuckoo nests created through levy flights from their positions as indicated as

$$nest_i^{t+1} = nest_i^t + \propto . S . \left(nest_i^t - nest_b^t\right). R, \tag{18}$$

Where $nest_i^t$ represents the current position of i^{th} nest, R is a standard normal distribution random number, $\propto$ is the step size parameter, $nest_b^t$ is the position of the best nest and S is a random walk based on the levy flights.

The levy flight provides a walk of random characteristics. The random step length is inspired from a levy distribution. One of the most efficient and yet straightforward ways of applying levy flights is Mantegna algorithm. The step length *S* in this algorithm can be determined by [33]

$$S = \frac{U}{|v|^{1/\beta}}, \tag{19}$$

where β is a parameter between (1, 2) and (*U*, *V*) are drawn from normal distribution as

$$U \sim n(0, \sigma_u^2), \tag{20}$$

$$V \sim n(0, \sigma_v^2), \tag{21}$$

$$\sigma_u = \left\{ \frac{\Gamma(1+\beta).sin\left(\pi.\frac{\beta}{2}\right)}{\Gamma\left[\frac{1+\beta}{2}\right].\beta.2^{\frac{\beta-1}{2}}} \right\}^{\frac{1}{\beta}}, \; \sigma_v = 1. \tag{22}$$

3.3. ALIEN EGGS DISCOVERY

The alien eggs are discovered using discovering probability matrix for each solution. This function is modeled as [33]

$$P_{ik} = \begin{cases} 1; & rand < P_a \\ 0; & rand \geq P_a \end{cases} \tag{23}$$

where P_a is the discovering probability. A good quality of new generated eggs will replace existing eggs from their current positions through random walks with step size as follows [33]

$$S = rand\big(nests(randprm1(n),:) - nests(randprm2(n),:)\big), \tag{24}$$

$$nest^{t+1} = nest^{t} + S.P, \tag{25}$$

where $randprm$ is a random permutation function used for different rows permutation applied on nests matrix, and P is the probability matrix.

3.4. TERMINATION CRITERION

The steps used to discover the alien eggs and generate new cuckoos are alternatively performed until a termination criterion is reached.

4. OBJECTIVE FUNCTION AND CONSTRAINTS FOR MG CONFIGURATION PROBLEM

The optimal MG configuration, that can supply a load, makes the best compromise between the CO_2 emissions and the energy cost to minimize the objective function with MG constraints through the lifetime of the system.

4.1. OBJECTIVE FUNCTION

The objective of the proposed approach is the design of an optimal MG configuration scheme that can feed the prescribed load under the suggested objective/fitness function with various constraints. The decision (optimization) variables are the number of wind turbines, PV modules, batteries, controller units, inverter units, and diesel generators. The number of the optimization variables is decided by the proposed approach, from various available components of different ratings which are given in the appendix. These variables constitute the numbers of equipment needed to supply the load at minimum investment cost. The objective/fitness function is proposed for reducing the system TIC within the MG system lifetime in the standalone mode. The mathematical model for the objective function can be formulated as [18]

$$TIC = \sum_{i=1}^{n_{WT}} N_{WTi}.C_{WTi} + \sum_{j=1}^{n_{PV}} N_{PVj}.C_{PVj} + \sum_{k=1}^{n_{BAT}} N_{BATk}.C_{BATk} + \sum_{l=1}^{n_{DG}} N_{DGl}.C_{DGl} + \sum_{m=1}^{n_{CON}} N_{CONm}.C_{CONm} + \sum_{y=1}^{n_{IVT}} N_{INVy}.C_{INVy}, \quad (26)$$

TIC should be minimized by a proper choice of the number of wind turbines (N_{WT}), PV modules (N_{PV}), batteries (N_{BAT}), diesel generators (N_{DG}), controller units (N_{CON}) and inverter units (N_{INV}). C_{WT}, C_{PV}, C_{DG}, C_{BAT}, C_{CON}, and C_{INV} represent the TICs of WT, PV, DG, battery, controller, and inverter, respectively. The techno-economic data of the commercial components used in this study are available in [25]. The TIC of DG comprises the capital (C_{Cap}), installation (C_{ins}), operating, maintenance per year ($C_{O\&M}$), fuel (C_f) and the CO_2 emissions (C_{em}) costs. However, the TIC for other MG components include capital (C_{cap}), installation (C_{ins}), and operation and maintenance ($C_{O\&M}$) costs. The TIC for the DG (C_{DG}), wind turbine (C_{WT}), PV (C_{PV}), battery (C_{Bat}), converter (C_{Con}) and inverter (C_{Inv}) are calculated as [18, 25]

$$C_{DG} = \left(\frac{C_{Cap\_DG}}{4} + C_{f\_DG}H_{Ann} + C_{O\&M\_DG}H_{Ann} + C_{em}\right)T_{lifetime}, \quad (27)$$

$$C_{WT} = C_{Cap_{WT}} + C_{Ins_{WT}} + T_{Lifetime}C_{O\&M\_WT}, \quad (28)$$

$$C_{PV} = C_{Cap\_PV} + C_{INS\_PV} + T_{Lifetime}C_{O\&M\_PV}, \quad (29)$$

$$C_{Bat} = C_{Cap\_Bat} + C_{Ins\_Bat} + C_{Rep\_Bat}N_{Rep\_Bat}, \quad (30)$$

$$C_{Con} = C_{Cap\_Con} + C_{Ins\_Con} + T_{Lifetime}C_{O\&M\_Con} + C_{Rep\_Con}N_{Rep_{Con}}, \quad (31)$$

$$C_{Inv} = C_{Cap\_Inv} + C_{Ins\_Inv} + T_{Lifetime}C_{O\&M\_Inv} + C_{Rep\_Inv}N_{Rep\_Inv}, \quad (32)$$

where T_{DG} is the daily hours of operation of the DG, H_{Ann} is the total number of hours that the DG can be used in one year ($T_{DG} \times 365$), $T_{lifetime}$ is the lifetime for the project (20 years) and N_{Rep} is the number of units replacements through the lifetime period.

In this paper, the lifetime of both PV modules and WT is supposed to be 20 years, the inverter and controller life time is 10 years, and the life time of the batteries is assumed to be 5 years [25]. The MG units replacement costs (C_{Rep}) are the same as their capital costs. As previously mentioned, C_{em} is calculated by a novel WGAF given by Eq. (8). The total number of units in the selected MG Configuration is provided in Table 1.

Table 1: Bounds for optimization variables of the units in the selected MG Configuration

Bounds	N_{WT}	N_{PV}	N_{Bat}	N_{DG}	N_{Con}	N_{Inv}
Minimum	0	0	0	0	0	0
Maximum	1	40	20	20	100	20

4.2. MG CONSTRAINTS

The total generation of yearly energy (kWh/year) must exceed or at least equal the effective annual energy consumption, which is the energy consumed by the yearly load divided by the efficiency of the overall system (η_{sys}). The energy balance and the overall system efficiency can be determined as [18]

$$\sum_i N_{WT}E_{WT} + \sum_j N_{PV}E_{PV} + \sum_j N_{DG}E_{DG} \geq \frac{E_{Load}}{\eta_{sys}}, \tag{33}$$

$$\eta_{sys} = \eta_{DG}\eta_{Bat}\eta_{Con}\eta_{Inv}\eta_{W}, \tag{34}$$

where E_{Load} represents energy consumption of the load, E_{WT}, E_{PV}, and E_{DG}, represent the energy generated by WTs, PV modules and DGs, respectively in (kWh/year), η_{sys}, η_{Inv}, η_{Con}, η_{W}, η_{Bat}, and η_{DG} represent overall efficiency of the MG system, inverter, PV controller, connection wires, battery, and DG efficiencies, respectively. The average efficiency for DG, battery, PV controllers, inverter, and wires, are shown in Table 2.

Table 2: Efficiencies (average) of the MG components

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

The bounds on the optimization variables of the MG system, the constraints regarding sizing of PV controllers and inverters and the constraints on the SOC of batteries are given by [18]

$$0 \leq N_{WT} \leq N_{WT\_max}, \tag{35}$$

$$0 \le N_{PV} \le N_{PV\_max}, \quad (36)$$

$$0 \le N_{DG} \le N_{DG\_max}, \quad (37)$$

$$\sum_{j} N_{Con} P_{Con} \ge P_{PV\_max}, \quad (38)$$

$$\sum_{i} N_{Inv} P_{Inv} \ge P_{max}, \quad (39)$$

$$\sum_{i} N_{Inv} P_{Inv} \ge P_{Inv\_max}, \quad (40)$$

$$SOC_{min} \le SOC \le SOC_{max}. \quad (41)$$

where N_{WT_max}, N_{PV_max}, and N_{DG_max} represents the maximum number of WTs, PV modules and DG units, respectively. P_{Inv}, P_{Con}, P_{max}, and P_{PV_max} represent the maximum output power (W) of inverter, PV controller, load and PV module, respectively. *SOC* is the state of charge of a battery.

DG should have operation time limits for reducing wear and tear. This limitation can be modeled by [26].

$$\sum_{T=1}^{T=24} T \le T_{DG}, \quad (42)$$

$$0 \le T_{DG} \le K. \quad (43)$$

where T_{DG} represents the time (hours) that the DG operates daily and T_{max} is the maximum permissible time that the DG operates per day.

The CO_2 emissions amount in kg is an indication and measurement parameter for the environmental pollutant emissions. It represents the percentage of the maximum CO_2 emissions in the fuel combustion process.

In this study, novel WGAF, described in section 2.3, is designed to investigate the impact of CO_2 limitation on the optimal system configuration and TIC. This is achieved by applying an increasing tax on the CO_2 emissions.

5. CASE STUDY AND IMPLEMENTATION

The case study is a typical isolated MG used 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 for obtaining the optimal configuration and energy management of the MG components that satisfy the objective/fitness function with the novel WGAF discussed previously. Input data includes the load data, meteorological data of the suggested location, and techno-economic data of the MG system components.

5.1 LOAD DATA

It is considered that outdoor and indoor lighting load for the educational building will be met by a MG system. Table 3 shows the daily electrical load requirements, with peak load of 50 kW. Using Table 2 and actual load measurements, a load profile is built as shown in Fig. 2. It shows the daily load profile for the proposed MG system with a maximum value of 50 kW and an average consumption of 516.724 kWh/day.

Table 3: Daily electrical load requirements

Parameters	**Entrance**	**Outdoor**	**Indoor**
Rated power (kW)	1.08	14.588	49.968
Operation period (h)	6	11	7
Daily energy(kWh/day)	6.48	160.468	349.776
Total daily energy (kWh/day)	516.724		

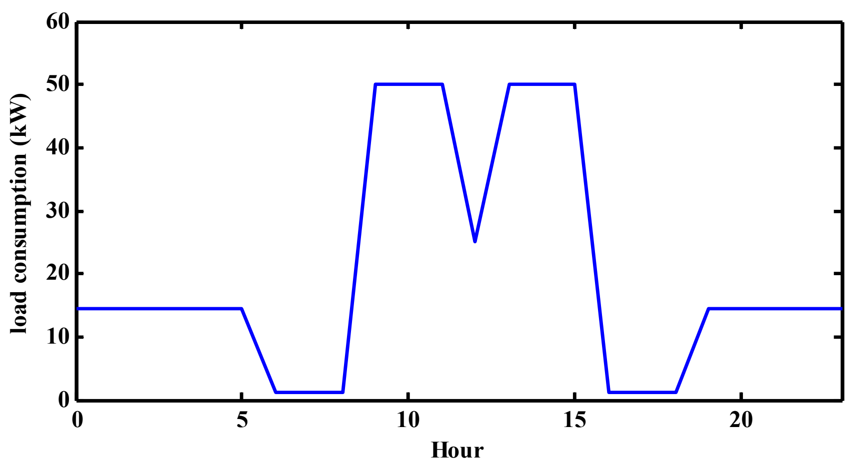

Fig. 2: Considered daily load profile

5.1.1. METEOROLOGICAL DATA AND TECHNO-ECONOMIC DATA

The solar radiation and wind speed (monthly average) are obtained from "NASA surface meteorology and solar energy" [16]. The monthly average irradiation and air temperature (°*C*), for the suggested location, incident on a horizontal surface, are indicated by Table 4 and Table 5, respectively. Table 6 indicates the average values per month of the wind speed at 50 m above earth's surface. As explained in Section 2.1, it is necessary to adjust the wind speed to the hub height if the speed is measured at a height different from that of turbine hub height. In this paper, the wind towers are measured at a height of 2 m, so that the measured wind speed values must be modified as shown in Table 7. The techno-economic data of the used commercial components in this study are available in [25].

Table 4: Monthly averaged irradiation 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	5.1
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 5: 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 6: Averaged wind speed/month at 50 m from the surface 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 7: 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	

5.2 IMPLEMENTATION OF CSOA

To apply CSOA in the MG configuration, each nest will be represented as a set of solutions, while the eggs will be represented as the number of PVs, WTs, DGs, PV controllers and batteries, seeking the best solution (nest) or the optimal MG configuration and energy management. As the optimization problem is non-convex, therefore, it is not possible to determine the existence of the solution analytically. Hence an extensive simulation study has been carried out, which satisfies all the constraints of the case study. The CSOA algorithm has been run for 20 independent trials with different settings until the solutions are very close to each other. Then, the best one has been selected for comparison. According to the trials, the basic CSOA parameters used herein are given in Table 8. The flow chart for the proposed optimization scheme using CSOA is shown in Fig. 3.

Table 8: CSOA parameters

Number of iterations	2000
Number of nests (n)	65
Discovery probability or alien eggs (Pa)	0.25
Step size parameter (α)	1

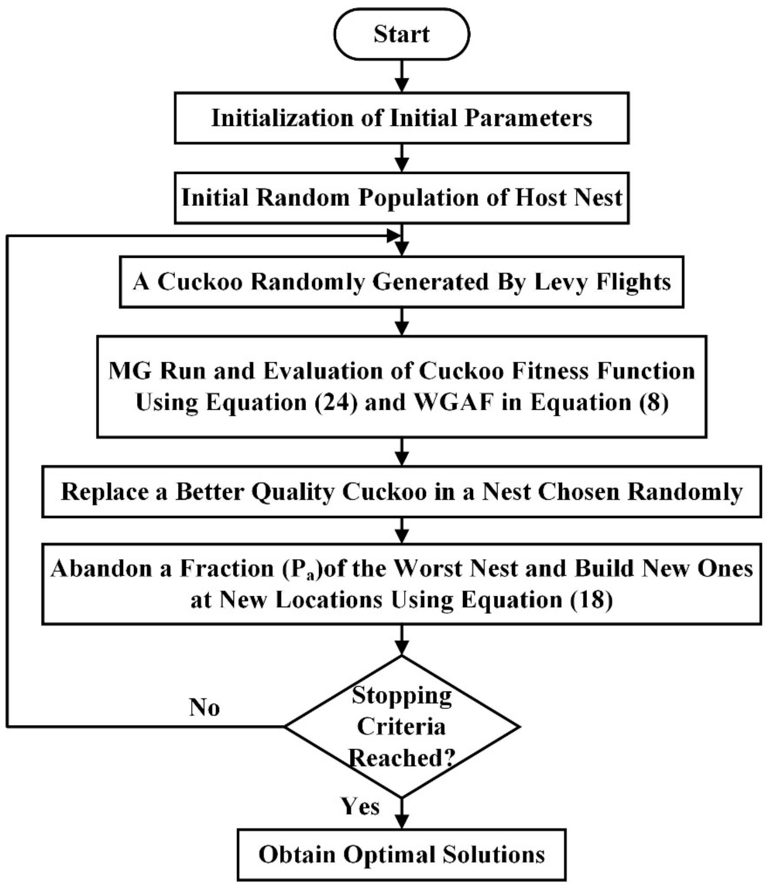

Fig. 3: CS method for optimal configuration

5.3 COMPARISON WITH BFOA

The MG configuration results obtained with the help of CSOA are compared with those obtained by BFOA discussed in [34, 35]. The BFOA algorithm has also been simulated for 20 independent trials with different settings until the solutions are very close to each other. According to the trials, the basic BFOA parameters are given in Table 9.

Table 9: BFOA parameters

Dimension of the search space (*p*)	65
Total number of bacteria (*S*)	100
Number of chemotactic steps (N_c) [4:10]	10
Swimming length (N_s) [2:4]	4
Number of reproduction steps (N_{re}) [4:10]	4
Number of elimination–dispersal events (N_{ed}) [1:4]	4
Elimination-dispersal probability (P_{ed}) [0.25]	0.25
Number of bacteria (splits) per generation (S_r)	4
Step size *c(i)* [<= 0.1]	2e-6

6. OPTIMIZATION RESULTS AND ANALYSIS

The optimum MG system configuration that meets the energy required by the previously mentioned load profile is obtained by performing the designed optimization scheme. The simulation results using CSOA and BFOA are discussed in the following subsections.

6.1. USING CSOA WITHOUT CO_2 EMISSIONS CONSTRAINTS

Table 10 lists different types of wind turbines, PV modules, diesel generators, inverters and controllers selected in the optimum MG configuration design without CO_2 emissions limitations. A group of batteries is also used to store the excessive energy in case the generation is higher than the load, and to supply energy in the opposite case scenario. In this case, the total generated energy is of 321614.6378637 kWh/year, whereas, the energy consumption is 321603.8851 kWh/year. The model represents a MG system configuration with a TIC value of $43931.6071with high CO_2 emissions of 13769.1544 kg.

Table 10: MG sizing optimization results using CSOA without CO_2 emission constraints

MG	Commercial type	Rated cap.	No.	Commercial type	Rated cap.	No.
wind	SouthWest (Air X)	400w	1	Bornay (Inclin 250)	250w	1
	SouthWest (Whisper100)	900w	1	Bornay (Inclin 6000)	6000w	1
	SouthWest(Whisper 500)	3000w	1	Kestrel Wind (600)	600w	1
	AeromaxEng(Lakota)	800w	1	Kestrel Wind (3000)	3000w	1
	Bergey (BWC 1500)	1500w	1	Solacity (Eoltec)	6000w	1
	Bergey (BWC Excel-R)	8100w	1	---	--	-
PV	Sharp ND-250QCS	250w	40	CSI CS6X-285P	285w	40
	Hyundai HiS-255MG	255w	40	Canadian Solar-250P	250w	40
	Lightway	235w	40	CSI CS 6X-295P	295w	40
	Trina TSM-PA05	240w	39	Canadian Solar-300P	300w	40
	Solartech SPM135P	135w	32	Canadian Solar-255M	255w	40
	CSI CS6P-235PX	235w	40	Hyundai HiS-260MG	260w	40
	CSI CS6X-280P	280w	40	---	--	-
Diesel	STEPHIL -SE 3000D	1900w	10	---	--	-
Bat.	Surrette 2Ks33Ps	1765Ah	10	---	---	-

Con.	SE-XW-MPPT-60	1500w	92	---	--	-
Inv.	SE-DR1524E	1500w	2	SE-XW4024	4000w	11
	SE-XW6048	6000w	1	---	--	-

6.2. USING BFOA WITHOUT CO_2 EMISSIONS CONSTRAINTS

The optimization results using BFOA without emission constraints are listed in Table 11. In this configuration, the total generated energy is 321738.9684 kWh/year, whereas, the consumed energy is 321603.8851 kWh/year. The TIC of MG system is $44193.1987 with CO_2 emissions of 13769.15449 kg.

Table 11: MG sizing optimization results using BFOA without emission constraints

MG	Commercial type	Rated cap.	No.	Commercial type	Rated cap.	No.
wind	South West (Air X)	400w	1	Bornay (Inclin 6000)	6000w	1
	South West (Skystream3.7)	1800w	1	AR (ARE442)	10000w	1
	Bergey (BWC Excel-R)	8100w	1	Kestrel Wind (800)	800w	1
	Bornay (Inclin 250)	250w	1	Kestrel Wind (3000)	3000w	1
	Bornay (Inclin 600)	600w	1	Solacity (Eoltec)	6000w	
PV	Sharp ND-250QCS	250w	38	CSI CS6X-285P	285w	40
	Hyundai HiS-255MG	255w	40	Canadian Solar-250P	250w	40
	Lightway	235w	40	CSI CS 6X-295P	295w	40
	Trina TSM-PA05	240w	40	Canadian Solar-300P	300w	39
	CSI CS6P-235PX	235	40	Canadian Solar-255M	255w	39
	CSI CS6X-280P	280w	40	Hyundai HiS-260MG	260w	40
Diesel	STEPHIL -SE 3000D	1900w	10	---	--	-
Bat.	Surrette 2Ks33Ps	1765Ah	10	---	--	-
Con.	SE-XW-MPPT-60	1500w	88	---	--	-
Inv.	SE-DR1524E	1500w	6	SE-XW4024	4000w	11

6.3. COMPARISON BETWEEN THE PROPOSED CSOA AND BFOA

A comparison between the results obtained by BFOA with those obtained by CSOA is provided in Table 12. The TIC, emissions levels, energy generated, and cost of energy are examined. The table also shows the seeking time of each technique for obtaining the optimum MG configuration.

Table 12: Optimization results using BFOA, and CSOA without CO_2 emissions limitations

Used Technique	CSOA	BFOA
Energy consumed by the load	321603.8851	321603.8851
Generated energy (kWh/year)	321614.6378	321738.9684
Surplus energy (kWh/year)	10.7527	135.0833
Wind energy (kWh/year)	45400.9129	55640.5882
PV energy (kWh/year)	240242.8910	230729.8802
Diesel Energy (kWh/year)	35368.5	35368.5
TIC ($/year)	43931.6071	44193.1987
Annual cost of energy ($/kWh)	0.1366016	0.137415
CO2 emissions (kg/year)	13769.1544	13769.1544
Seeking time (sec)	49.9	112.4

It is obvious from Table 12 that the results of the MG configuration via CSOA are better than that obtained by BFOA with respect to TIC, annual cost of energy, and seeking time. It is also clear that the optimized MG configuration using CSOA shows high robustness properties with respect to load constraints. Also, the optimization scheme tends to select PV with numbers which are higher than DG and WT. According to these results, it can be concluded that the selected site has good temperature and irradiations.

6.4. USING CSOA CONSIDERING THE CO_2 EMISSION LIMITS

In this subsection, impacts of limiting the CO_2 emissions on the TIC, annual cost of energy, energy generated by MG generation sources, and % change in CO_2 emissions are examined. Table 13 shows the results of the MG configuration considering the novel proposed function explained in section 2.3. Figures 4, 5 and 6 show the monthly energy generated in a year by different MG generation sources with different coefficients of WGAF.

Table 13: Impact of CO_2 emissions limiting using the proposed WGAF

Used technique / **Item**	**CSOA**				
Proposed limiting function coefficients	C_1 =0 % & C_2 = 0 %	C_1 = 5% & C_2 = 5%	C_1 = 5% & C_2 = 10%	C_1 = 5% & C_2 = 50 %	C_1 = 5% & C_2 = 100 %
Energy required by the load	321603.8851	321603.8851	321603.8851	321603.8851	321603.8851
Generated energy(kWh/year)	321614.6378	322360.2299	321901.7772	322476.4110	321883.5582
Surplus energy (kWh/year)	10.7527	756.3448	297.8921	872.5259902	279.6731270
Wind energy (kWh/year)	45400.9129	63696.8033	65654.3882	67235.51459	71828.31010
PV energy (kWh/year)	240242.8910	230368.6266	231489.4389	237556.6464	235.9078481
Diesel Energy (kWh/year)	35368.5	28294.8000	24757.95000	17684.25000	14147.40000
Numbers of DGs	10	8	7	5	4
TIC ($/year)	43931.6071	44055.1225	44012.6346	44352.7181	48544.7398
% Change in TIC	base	+0.28115383	+0.18444020	+0.95856063	+10.5007148
Energy/year cost of ($/kWh)	0.1366016	0.13698566	+0.13685355	0.137911014	0.15094575
CO_2 emissions in (kg/year)	13769.1544	11015.3235	9638.4081	6884.577247	5507.661797
% Change in CO2 emissions	base	-20	-30	-50	-60

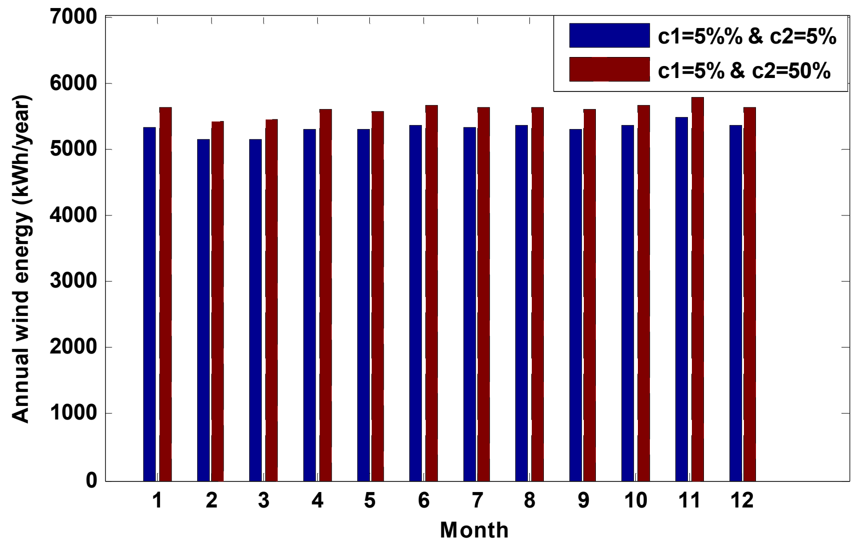

Fig. 4: Monthly wind energy with increasing coefficients using CSOA

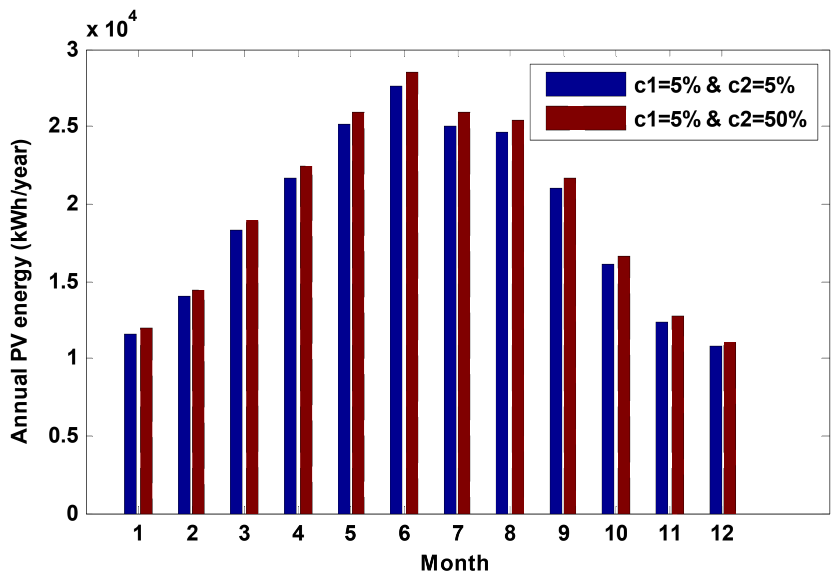

Fig. 5: Monthly PV energy with increasing coefficients using CSOA

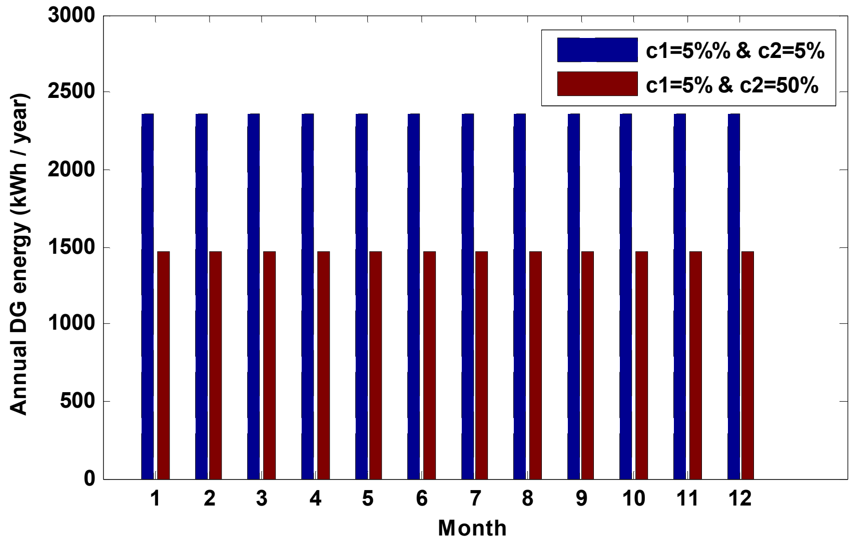

Fig. 6: Monthly DG energy with increasing coefficients using CSOA

It can be concluded from the above results that by increasing the WGAF coefficients (c_1, c_2), the number of diesel generators and hence the CO_2 emissions is decreased. As a result, the energy required from WTs and PVs is increased and consequently the numbers of wind turbines, PV modules, PV controllers, and batteries are increased. This will increase the installation cost of the system in addition to the increase in cost of CO_2 emissions and accordingly the system TIC is increased. In addition, results indicate that the case used with c_1 = 5% and c_2 = 100% is the least economical configuration, with +10.5007148% increase in TIC. However, the highest CO_2 emission reduction of 60 % has also been achieved in this case. The case with c_1 = 5% and c_2 = 50% is the optimum with 50 % CO_2 emissions reduction and negligible increase in TIC of +0.95856063%.

6.5. MG ENERGY MANAGEMENT

While designing and simulating the proposed MG, it has been assumed that the grid is isolated and is supplying rated energy to the load throughout the project lifecycle. Table 13 shows that the MG system configuration, with a TIC of $44352.7181 and 50% decrease in CO_2 emissions, represents the most economic option with lower emissions. Thus, this configuration is used for the MG and supplying the annual average load described in subsection 5.1.1. Fig. 7 shows a share of the designed individual MG components in supplying the load profile, whereas Fig. 8 indicates the monthly share of combined components and Fig. 9 indicates the charged and discharged energy in batteries over 12 months.

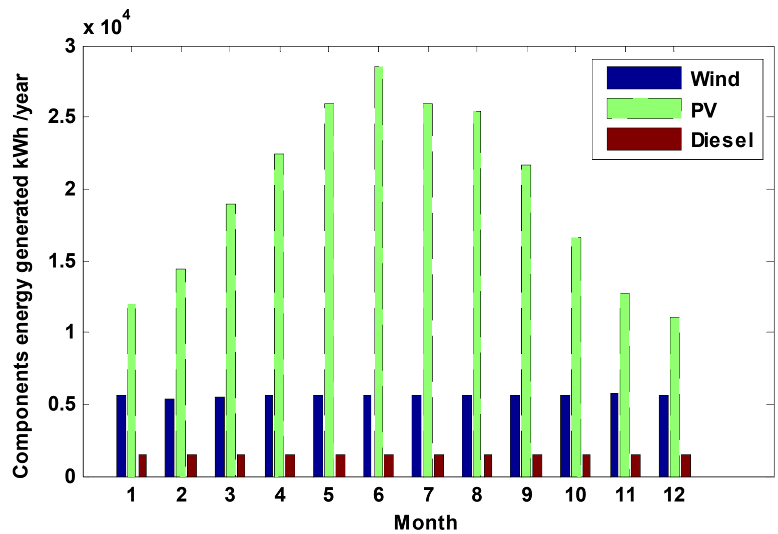

Fig. 7: Load profile sharing using MG components with $C_1 = 0.05$ and $C_1 = 0.5$

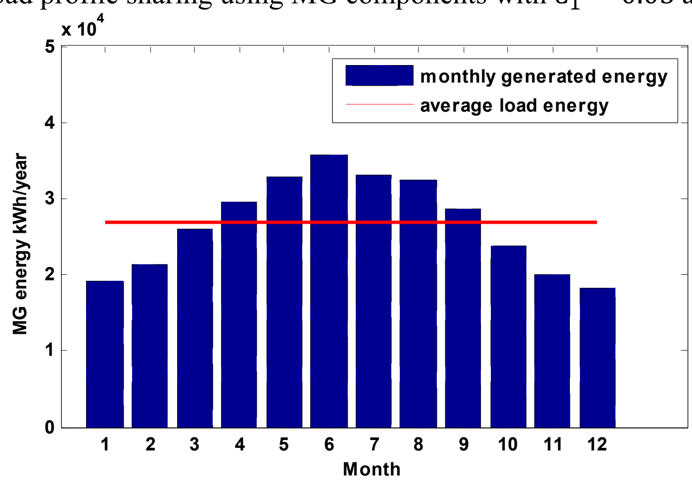

Fig. 8: Grouped load profile sharing with $C_1 = 0.05$ and $C_1 = 0.5$

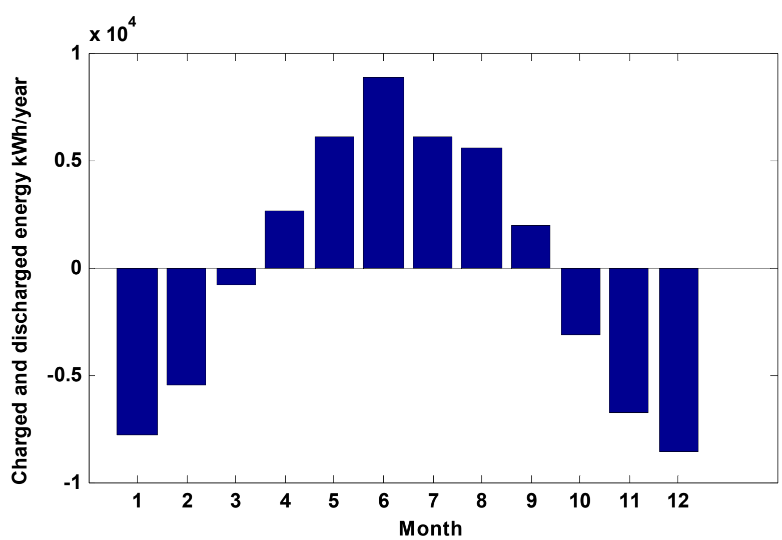

Fig. 9: Surplus energy lost in batteries with $C_1 = 0.05$ and $C_1 = 0.5$

It is evident from Fig. 7, 8 and 9 that with a limitation of CO_2 emissions, the DGs share the smallest part of the load profile energy. In addition, the share of WTs in energy production is not significant due to low wind speed profile. The components of the MG generate higher energy in April to August as the irradiations and temperature of the selected site are higher during these months. The results also show that PV technology is preferable in this location.

7. CONCLUSION

In this paper, an optimal configuration and energy management scheme of MG components supplying a load is constructed and designed. The objective of minimizing the TIC with a novel WGAF to limit CO_2 emissions by applying higher tax on the increasing emissions that exceed the governmental approved limits is achieved. Limitations are also added to take into consideration some of the additional conditions found in an isolated MG generation system. The results show that the proposed optimization scheme is efficient and robust. In addition, the configuration scheme is optimized using CSOA and BFOA. The CSOA is simpler than BFOA in implementation and it also yields better results and consumes less time. Moreover, the CSOA is more robust against parameter adjustment and number of parameters. The use of novel WGAF results in reduction of CO_2 emissions to around 50% with negligible cost increase of about (+0.9585 %.), which emphasizes that the designed MG has economically great benefits with low environmental hazards.

8. Declarations of interest: none

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Appendix

Table A: Photovoltaic panels techno-economic data

Model	P_{out} (W) at STC	$C_{cap.}$ in $	$C_{ins.}$ in $	$C_{o\&m}$ in $/year
Sharp ND-250QCS	250	240.00	108.000	6
Hyundai HiS255MG	255	229.50	103.2750	5.7375
Lightway	235	157.45	70.8525	3.9362
Trina TSM-PA05	240	165.60	74.5200	4.1400
Solartech SPM135P	135	359.10	161.5950	8.9775
CSI CS6P-235PX	235	169.20	76.1400	4.2300
CSI CS6X-280P	280	207.20	93.2400	5.1800
CSI CS6X-285P	285	219.23	98.6535	5.4807
Canadian Solar CS6P	250	198.75	89.4375	4.9687
CSI CS6X-295P	295	244.85	110.1825	6.1212
CanadianSolarCS6X300P	300	249.00	112.0500	6.2250
CanadianSolarCS6P255M	255	230.77	103.8465	5.7692
Hyundai HiS-260MG	260	238.80	107.1360	5.9520

Table B: Wind turbines techno-economic data

Model	P_{out} (W)	$C_{cap.}$ in $	$C_{ins.}$ in $	$C_{o\&m}$ in $/year
Southwest -Air X	400	248.985	74.6955	24.8985
Southwest -Whisper 100	900	844.985	253.4955	84.4985
Southwest -Whisper 200	1000	1000	300	100
Southwest -Whisper 500	3000	3076.391	922.9173	307.6391
Southwest -Skystream 3.7	1800	1824.470	547.341	182.447
AeromaxEng.Lakota	800	412.820	123.846	41.282
Bergey -BWC 1500	1500	1706.315	511.8945	170.6315
Bergey-BWC XL.1	1000	1494.57	448.3710	149.4570
Bergey -BWC Excel-R	8100	11198.43	3359.529	1119.8430
Bornay -Inclin 250	250	165.4001	49.62003	16.5400
Bornay -Inclin 600	600	394.3901	118.3170	39.4390
Bornay-Inclin 1500	1500	2792.885	837.8655	279.2885
Bornay-Inclin 3000	3000	4191.035	1257.311	419.1035
Bornay-Inclin 6000	6000	6783.701	2035.110	678.3701
Abundant R-ARE110	2500	2740.001	822.0003	274.0001
AbundantRR-ARE442	10000	13199	3959.700	1319.900
Kestrel Wind-600	600	844.920	253.4760	84.4920
Kestrel Wind-800	800	986.240	295.8720	98.6240
Kestrel Wind-1000	1000	1545.135	463.5405	154.5135
Kestrel Wind-3000	3000	3001.125	900.3375	300.1125
Solacity-Eoltec	6000	7497.5	2249.250	749.7500

Table C: Batteries techno-economic data

Type	Ah	C_{cap} in $	C_{ins} in $	C_{rep} in $
MK 8L16	370	1749.3	35.7	1749.3
Surrette 12-Cs-11Ps	375	6851.425	139.825	6851.425
Surrette 2Ks33Ps	1,765	5434.492	110.908	5434.492
Surrette 4-CS-17PS	546	3935.925	80.325	3935.925
Surrette 4-Ks-21Ps	1,104	6804.777	138.873	6804.777
Surrette 4-Ks-25Ps	1350	8524.922	173.978	8524.922
Surrette 6-Cs-17Ps	546	5551.112	113.288	5551.112
Surrette 6-Cs-21Ps	683	6501.565	132.685	6501.565
Surrette 6-Cs-25Ps	820	7784.385	158.865	7784.385
Surrette 8-Cs-17Ps	546	7492.835	152.915	7492.835
Surrette 8-Cs-25Ps	820	10350.03	211.225	10350.03
Surrette S-460	350	1976.709	40.341	1976.709
Surrette S-530	400	2186.625	44.625	2186.625
Trojan L16H	420	2099.160	42.840	2099.16
Trojan T-105	225	991.270	20.230	991.27
US Battery US185	195	1667.666	34.034	1667.666
US Battery Us2200	225	1032.087	21.063	1032.087
US Battery US250	255	979.608	19.992	979.608
Surrette S-460	350	1749.300	35.700	1749.3
Surrette S-530 6V	400	1900.906	38.794	1900.906

Table D.: Controller techno-economic data

Type	P_o(W)	C_{cap}($)	C_{ins}($)	$C_{O\&M}$($/y)	C_{rep}($)
S.E.-XW-MPPT-60	1500	248	4.96	0.745335	248
Outback FM 80	2000	335	6.70	1.005000	335
Outback FM 60	1500	280	5.60	0.840000	280
S.E. XW-MPPT-80	2,000	580	11.60	1.739835	580
Blue Sky SB3048	750	173	3.46	0.519000	173

Table E: DG techno-economic data

Type	Po(KW)	C_{cap}($)	$C_{O\&M}$($/h)	FC(L/h)	Lifetime(h)
STEPHIL-SE3000D	1.9	1713.15	0.2	0.7	8760

Table F: Inverter techno-economic data

Type	P_o(W)	C_{cap}($)	C_{ins}($)	$C_{O\&M}$($/y)	C_{rep}($)
S.E. DR1524E	1,500	350	7.15	1.95	350
S.E. XW6048	6,000	1518	30.3750	4.60000	1518
S.E.XW4548	4,500	1216.43	24.3286	3.64929	1216.43
Outback FX2024ET	2,000	654.50	13.0900	1.96350	654.50
S.E. XW4024	4,000	812.05	24.2386	2.43615	812.05