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Using genetic algorithm for optimal sizing of stand-alone hybrid energy system

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Abstract
When planning a hybrid energy system (HES) that incorporates both renewable and non-renewable energy sources—those that rely on fossil fuels—the primary considerations are the total cost of the system and the CO_2 emissions. In this paper, we will investigate the typical hybrid energy system (HES) that incorporates both renewable and non-renewable energy sources involving a detailed simulation process that may require specific inputs, models, and data. Then, we employed dual optimization methods: genetic algorithm (GA) and particle swarm optimization (PSO). The consequences of GA and PSO execution in the bus timetabling problem depict that the GA algorithm is better at finding the optimal solution in terms of accuracy and iteration. Additionally, the GA algorithm is also superior to the straightforwardness of the techniques used. So, in this work, we employed a Genetic Algorithm Optimization (GA)-–based optimal sizing technique for HES configurations that include sustainability wind turbines (WTs), battery storage (BS), and diesel generators (DGs). HES improved power delivery to a rural community in the Wasit Province, Iraq, situated at 46° - 36° and 32° - 31° in the country's southeastern central region. Throughout the project's 25-year lifespan, the optimization primarily aims to minimize the total cost (CT) and total CO_2 emissions (ECO2T). The outcomes demonstrate that the GA algorithm may, with continuous electricity supply, minimize the objectives while meeting the load demand.

Keywords: Sustainable energy, Wind energy, Genetic algorithm optimization

1. Introduction

Powering the globe now and tomorrow is one of the most pressing problems facing humanity. Lately, there has been a global demand for a substantial quantity of energy. Coal, crude oil, and natural gas are the only conventional energy sources today [1]. Additionally, there is a strong demand for fossil fuels due to the ever-increasing energy demand [2, 3]. These resources are scarce, and their distribution is not uniform across the Earth's surface. The potential of subsequent generations to achieve electrical sustainability is impacted by these factors [4-8]. In recent years, climate change and global warming have emerged as major environmental and economic concerns, with obvious implications for the upward trend in energy prices [9-11], especially using microwave devices or special plants. Concerns about climate change, global warming, and energy supply have grown in tandem with the world's excessive energy consumption [12-21]. Bringing electricity to far places via transmission lines is a huge hassle and a waste of money. Due to factors such as steep terrain, high costs of grid extension, and the lack of reliable electrical infrastructure in outlying locations, alternative energy sources must be considered. For these areas, the HES is an effective means of supplying energy [22-27]. A major renewable energy source is wind power, which is especially useful in more remote places. Conventional units see a substantial drop in maintenance costs and a general decrease in fuel expenses overall. Wind power is an ideal solution for the increasing energy needs of many nations because it is renewable, environmentally friendly, and never-ending [28-31]. Additionally, it has established itself as a prominent energy source and is becoming increasingly influential in many nations. The average cumulative growth rate of wind capacity was around 28% between 1995 and 2010. The total installed capacity of commercial wind power plants increased by more than 400% between 2000 and 2020, reaching 240 GW across 80 nations. In 22 nations, almost 2,000 MW have been put into operation [32]. There is an urgent need to accelerate the deployment of wind energy and promote policies globally, but there is also a high demand for investments in wind power and many unfinished projects. The installed wind capacity will reach 1,000,000 MW by the end of the 2020s, according to sources [33-35].

Wind power's biggest drawback is that it's not constant. An environmentally beneficial and reliable answer to this problem is a hybrid energy system (HES), which combines several energy sources. It is recommended that the HES integrate a variety of sources, such as RESs with diesel generators and batteries, to enhance system stability and mitigate volatility. Recent years have seen an influx of software like HOMER, HYBRIDS, PVSYST, SOLSIM, and RAPSIM dedicated to optimizing RES systems with storage systems and diesel generators. However, due to the computational methods needed to address these methods' limitations, a significant amount of processing time is required [36-39]. For practical optimization problems, metaheuristic algorithms are now the go-to tool for finding the best possible solution. In addition, stochastic operators are a key differentiator for these types of methods compared to deterministic algorithms, which consistently find solutions to specific problems using similar starting points. Furthermore, meta-heuristic algorithms have several technical applications that validate their optimization capabilities [40-46]. This study minimizes the total cost of the system and total emissions of CO2 (ECO2T) using the Genetic Algorithm method, a metaheuristic algorithm.

2. Methodology

Accurate analysis of the operational actions of many scenarios is essential for any HES project evaluation, which in turn requires realistic requirements for the selected area. The following theoretical frameworks have been employed in this investigation:

2.1. HES project evaluation without optimization

Based on provided MATLAB code for simulating a hybrid energy system (HES), the scenario has been as follows:

1. Energy sources
   The HES includes three main energy sources: solar power, wind power, besides diesel power. The respective power capacities for each source are based on:
   - Solar Power: 100 watts
   - Wind Power: 50 watts
   - Diesel Power: 80 watts
2. Load profile: The hourly load analysis profile given in the sample has dissimilar loads for an hour in 24 hours. The pattern operating of the system holds the energy consumption data at 24-hour intervals.
3. Energy generation
   - Solar energy: Putting in tune with the solar capacity fluctuations and electricity quantities coming from the solar power sources.
   - Wind energy: Wind energy generated randomly with wind power capacity is used to compute the wind energy responsibility.

- Diesel energy: Continuity of power generation at a diesel capacity in situations when the supply of energy from renewable sources is limited.

4. Energy balance

   The hourly production of the solar, wind, and diesel sources is added together to determine the total energy generated. The power of the load profile is regarded as the energy demand of the system.

5. Visualization

   The first plot presents the comparison of the total energy produced and the energy consumed by the load profile over 24 hours. The next plot is the energy generation from different sources (solar, wind, and diesel) stacked for each hour.

6. Cost and emissions calculation

   Based on these preset cost and emissions values, an energy provider can estimate the costs and emissions arising from using each energy source. The total price and emissions from the hypothetical power generation get added up, and the results are shown.

   This is an initial demonstration of a hybrid energy system that commissions both renewable energies (solar and wind) and non-renewable (diesel) sources. The baseline showcases the energy production from different sources coupled with a load profile to meet its demand level within costs and emissions considerations associated with these energy sources.

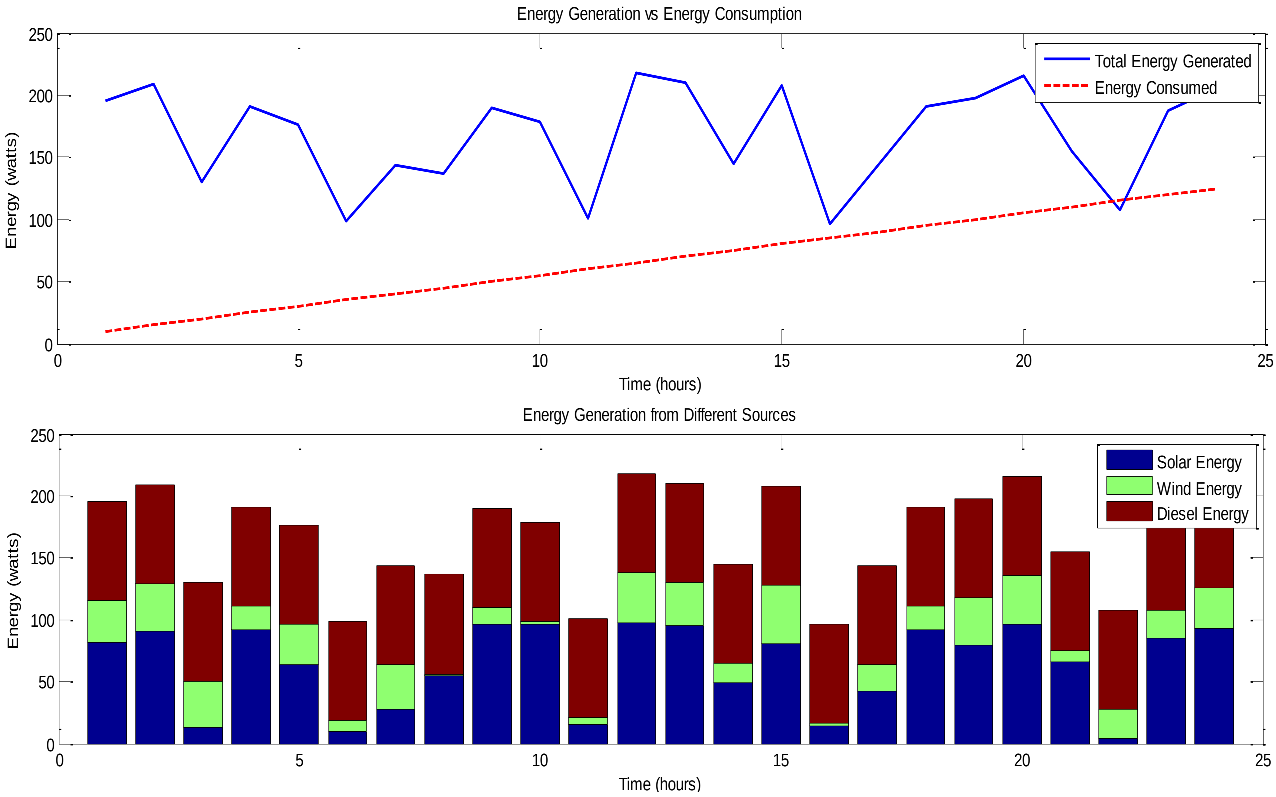

Figure 1. The energy generation from various resources, comparing them with the load profile, and also calculating the total cost and emissions that respect the defined cost as well as emissions values.

2.2. GA and PSO algorithms

The comparative analysis of the obtained outcomes by the Genetic Algorithm (GA) and the Particle Swarm Optimization (PSO) for the cost minimization problem is an avenue for some facts are explained in Figures 2-3. The total cost attained in each optimization method is the thing that would be analyzed. The general cost of "GA" is cost_ga, while the total cost of a "PSO" is denoted as cost_pso.

Similarly, assessing the accurate amounts of materials is one essential aspect of the efficiency of each technique. The amounts of Material 1, Material 2, and Material 3 through the GA that are compared with those through PSO are analyzed. These components will be referred to as x_ga(1), x_ga(2), x_ga(3) for GA and x_pso(1), x_pso(2), x_pso(3) for PSO.

Comparison between GA and PSO is given in the form of bar graphs which chart the costs in total amount obtained by each method. Apart from that, the equilibrium quantities of materials for GA and PSO are presented using darker individual bars to perform a more detailed analysis.

Overall, to decide which technique outperforms the others in this cost-minimizing issue, the total cost produced by each method should also be analyzed. The method that delivers a lower overall cost is TV more efficient and the best way to solve optimization equations.

After the comparison of the total cost and the optimized material quantity between the two methods, a decision can then be made for the method that minimizes the cost of materials optimization. The consequences of GA and PSO use in the bus schedule planning issue display that the GA algorithm is better than the PSO one by its precision and count of repetitions. Furthermore, the GA algorithm is efficient and straightforward to use.

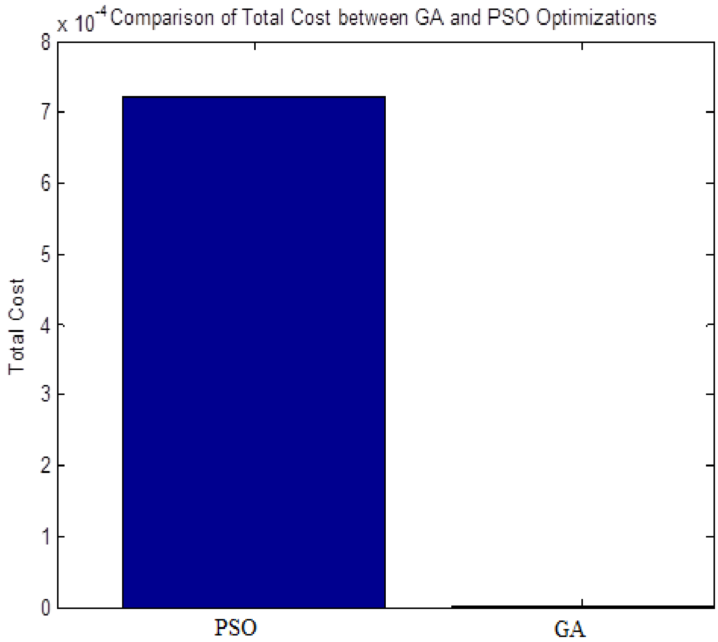

Figure 2. GA and PSO comparison in terms of total cost

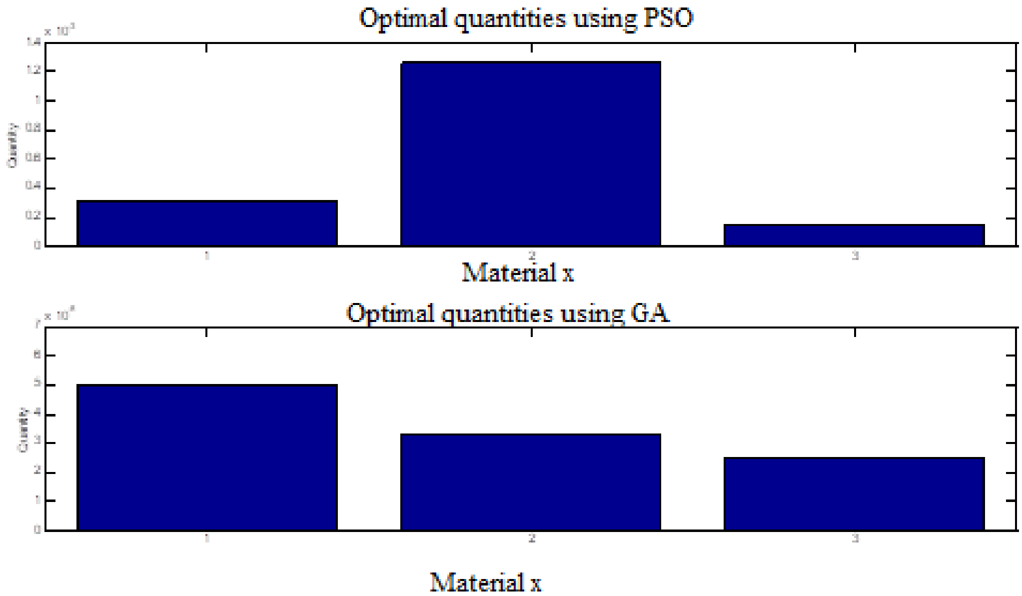

Figure 3. GA and PSO comparison in terms of optimal quantities

Within the material cost minimization problem, the word "material," refers to the various categories of resources or parts utilized in a specific procedure or manufacturing system. In this scenario, consider three specific materials: Material 1, Material 2, and Material 3.

Each material has related costs and restrictions that come with its use, availability, or other properties that are essential in calculating the cost of the process. The objective of this optimization problem is to find out the minimal cost by using the optimum quantities of these materials while all stated constraints are met. The quantity of Material 1, Material 2, and Material 3 are decision variables of the optimization problem. GA and PSO are selected to discover the optimal for these parameters that implies the minimum cost. Thus, in the comparison of GA and PSO results, we will explore how each optimization technique works to find the optimal material quantities that result in cost minimization. The optimized quantities of materials, in effect, have a great influence on the overall cost and efficiency of the optimization itself.

1. Scaling: A typical case in optimization problems is that the variables are scaled to a small range in order to ease the convergence and stability of the optimization algorithm. Shrinking the material values to small numbers will hinder numerical instability and enhance the optimization process's effectiveness.
2. Cost sensitivity: The price of the materials is likely to be comparatively small compared to other costs that are associated with implementing or running the process or system. In other cases, however, the focus of the problem could be to rather minimize other significant costs such as labor, energy, or other overheads, while the material costs in this case may be minor.
3. Unit cost: The prices provided here are indicative only and are based on the unit cost of each material. If the specific cost of a certain good is low, then the impact of this material would also be relatively small on the total cost.
4. Simplification: Moreover, the complication of the problem could be lessened by making use of small quantities of the material, to make it easier to grasp and visualize.

Generally, the small values assigned to materials in the cost minimization problem may be a result of various considerations such as scaling, cost sensitivity, unit cost, and simplification of the problem. These small values represent the material costs in the optimization process and facilitate the search for optimal solutions.

2.3. Specifying and loading the selected site profile

The Iraqi district of Kut, Wasit is home to the chosen isolated rural village for this study. Around 125 people are living in the 25 homes that make up the town. Because of this, there may be fresh chances to utilize standalone HES to power the region. Based on a full year's worth of data received from the Wasit Electricity Distribution Directorate, the average load was 80.224 kW and the peak load was 150 kW. Here is an explanation of the load demand for the first ten days of August, as illustrated in Figure 4.

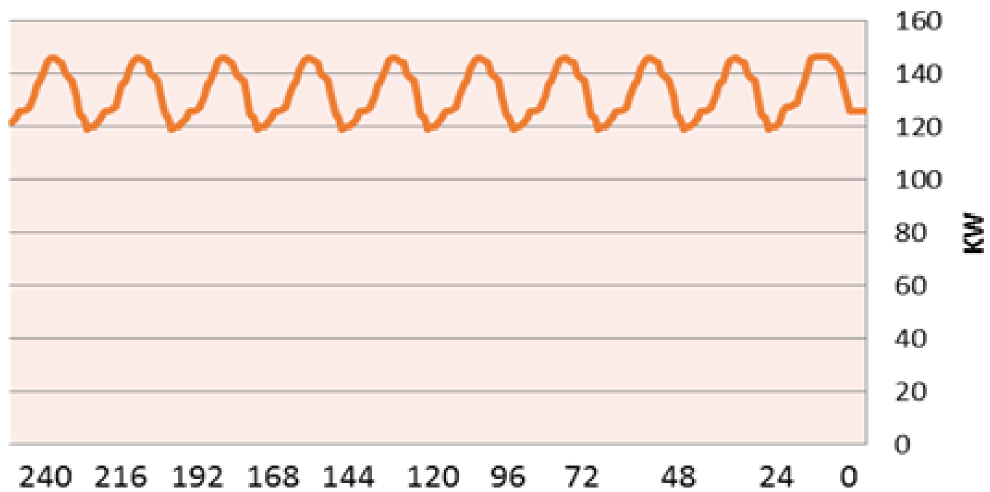

Figure 4. Load demand for the first ten days of August

2.4. Meteorological data (wind speed)

We gathered data from the weather prediction in Wasit every hour of the year because the output power of the WT is reliant on the wind speed at the hub height. Wind speeds of 4.5 m/s at a height of 10 m are typical in the Wasit Province, also known for its high levels of sun radiation. For clarification, Figure 5 displays the wind speed at 10 m in the first ten days of August.

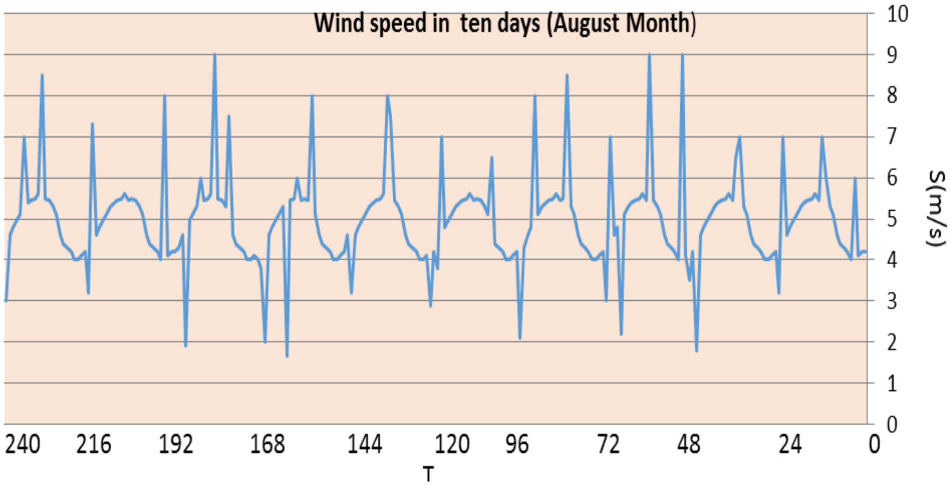

Figure 5. Wind speed for the first ten days in August

2.5. Proposed HES structure

The HES in this study consists of three parts: the power supply, the transformer, the bidirectional inverter, and the maximum power point tracking (MPPT) system, which converts AC to DC, DC to AC, and DC to DC, respectively. A schematic of the suggested HES is displayed in Figure 6.

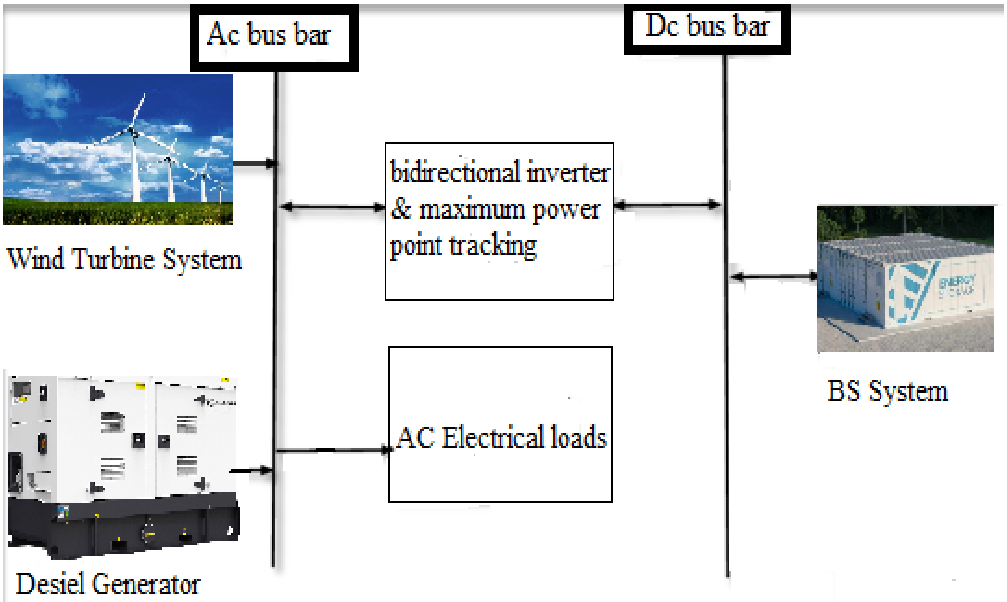

Figure 6. Block diagram for a proposed HES

2.6. Mathematical model

2.6.1. WT model

First, we need to convert the wind speed at reference height to wind speed at hub height using the following equation [47] since the WT's output power is dependent on the wind speed at hub height.

$$\text{parentS}(t) = S_{ref}(t) \times \left(\frac{h_{hub}}{h_{ref}}\right)^{\left(\frac{1}{7}\right)} \quad (1)$$

The given equation can be paraphrased as follows: S(t) is the wind speed at the hub height in m/s, S_ref (t) is the wind speed at the reference height in m/s, h_hub is the hub height for the WT in m, and h_ref is the reference height in m. The study uses a reference height of 10 meters and a WT hub height of 15 meters.
The output power of the WT in time (t) calculated by Equation 2.

$$P_{WT}(t) = \begin{cases} 0 & S(t) \le S_{cin} \quad \text{or} \quad S(t) \ge S_{cout} \\ P_r \times \left(\frac{S(t)-S_{cin}}{Sr-S_{cin}}\right) & S_{cin \le V(t)} \le Sr \\ P_r & Sr \le S(t) \le S_{cout} \end{cases} \tag{2}$$

Where: S_{cin} stands for cut-In wind speed (m/s), S_{cout} stands for cut-out wind speed (m/s), Sr stands for rated wind speed (m/s), P_r stands for rated power of the WT (W), and $S(t)$ stands for the instantaneous wind speed in the hub height (m/s).
Table 1 displays the WT parameters utilized in this research [48].

Table 1. WT parameters

Type	S_{cin}	Sr	S_{cout}	P_r	h_{hub}	Life Span	Maintenance cost	Investment Cost
Sunning Wind Power Ltd	3 m/s	12 m/s	20 m/s	5000 W	15 m	20 years	10 $/year	3000 $

2.6.2. BS model

In cases when the surplus of energy produced by the RESs exceeds zero and the current on the battery (COB) is lower than its maximum value (COB(t)

$$COB(t) = COB(t-1) \times (1 - Sd) + (E_{RES}(t) - \frac{E_D(t)}{\varepsilon_{inv}}) \times \varepsilon_{BS} \tag{3}$$

$$E_{S/D}(t) = E_{RES}(t) - \frac{E_D(t)}{\varepsilon_{inv}} \tag{4}$$

Where: $COB(t)$ stands for level charging for BS in a current hour (Wh), $COB(t-1)$ stands for level charging of the BS in the previous hour (Wh), Sd stands for a self-discharge rate for BS in hour (%), $E_{RES}(t)$ stands for the energy that generated of the RESs in time (Wh), $E_D(t)$ stands for the load demand of the energy in time (t) (Wh), ε_{inv} stands for inverter efficiency (%), ε_{BS} stands for BS efficiency (%), $E_{S/D}(t)$ stands for a surplus or a deficit of the RESs (Wh), COB_{max} stands for maximum level charging of the BS [Wh]

The BS discharge happens only when $E_{S/D}(t) > 0$ and $COB(t) < COB_{min}$, so $COB(t)$calculated by using Equation 5 [49]:

$$COB(t) = COB(t-1) \times (1 - Sd) + (E_{RES}(t) - \frac{E_D(t)}{\varepsilon_{inv}}) \tag{5}$$

Where: COB_{min} stands for minimum level charging of the BS (Wh)

The parameters of the BS used in this study were UKSOLAR BATTERY 12V and specified with a maximum capacity (NC_{Max}) for BS (Wh) is 2400 Wh, max allowed depth (MAD) of BS discharge (%) is 0.4× C_{Max}, BS efficiency (%) is>=90%, maximum and minimum level charging for BS (COB_{max} , COB_{min}) are (2400 Wh and 960 Wh) respectively, self-discharge rate for BS (Sd) is 1.488×10^{-2} and the investment cost is 245$.

The life span of the battery depends on the DOD as presented in Table 2.

Table 2. Life Span of the BS

MAD	At 20 %	At 30 %	At 40 %	At 50 %	At 60 %	Expected life in ideal float condition
Life Span	3500 cycles	3600 cycles	2400 cycles	1400 cycles	1000 cycles	10 years

2.6.3. DG model

When renewable energy sources (RES) are unable to meet demand and the cost of batteries (COB) is low, DG is required to provide a continuous load supply. Although the DG is climate-independent in terms of electricity supply, it does produce harmful byproducts during operation, such as CO2, which contribute to environmental pollution. The expense of upkeep is likewise quite significant. Equation 6 relates the fuel consumption of a DG to its nominal power and average output power, as shown by references [50, 51].

$$F_{cons}(t) = (0 \cdot 246 \times P_{Odg}) + (0 \cdot 08415 \times P_{Ndg}) \quad (6)$$

Where: $F_{cons}(t)$ stands for the fuel consumption of a DG in time (t)(L/h), P_{Odg} stands for an average output power for DG (kW), P_{Ndg} stands for a nominal power for DG (kW). All of the DG parameters used in this investigation are listed in Table 3.

Table 3. DG parameters

Type 1	Model	P_{Ndg}(kW)	P_{Odg}(kVA)	Phase	Frequency	Maintenance cost	Life span	Investment cost
Perkins	1106A-70TAG2	120 kW	150 KVA	3	50 HZ	0.309 $/h	15000 h	20000$

2.6.4. Inverter model

Equation 7 is used to determine how many inverters are required for the HES.

$$N_{INV} = \frac{P_{M-HES}}{P_{M-Inv}} \quad (7)$$

Where: P_{M-HES}, the maximum power created by linked components with the inverter(INV) has expressed [W]. P_{M-Inv} is the maximum inverter capacity [W].

The inverter model employed in this paper where uses the MPI HYBRID SERIES model and the parameters for the Inverter are: max .efficiency is 91%, maximum invertor 10 kW, frequency is 50/60 Hz, maintenance cost is 25$/year and investment cost 3400 $.

3. The adopted algorithm

The optimization aims to minimize total CO_2 emissions (ECO2T) while providing a continuous electrical load (reliability as a constraint) and to find the optimal sizing of HES (WT, DG, and BS) to lower the system cost (CT), which in turn lowers energy costs (COE). Every element of the three-row vector (x 1 to x 3), which specifies the number of subsystem components needed in HES, makes up the typical system configuration X. Therefore, the N-row vector is displayed:

$$X = [x_1 \;\; x_2 \;\; x_3 \,] \quad (8)$$

$$0 \le [x_1 \;\; x_2 \;\; x_3 \,] \le max \quad (9)$$

Where x_1 is the number of WT needed by the HES, x_2 is the number of BS needed by the HES, and x_3 is the number of DG needed by the HES. In cases when CT is determined using Equation 10,

$$CT = CIT + CRT + CMT + CFT \quad (10)$$

Where: CT stands for the total investment cost for the system ($), CRT stands for the total replacement cost of the system ($),$CMT$ the total maintenance cost for the system ($),$CFT$ stands for total fuel cost for DG ($), through the life cycle of the project (25 years). Reducing CT would lessen an energy cost (COE) based on Equation 11.

$$COE = \frac{CT}{\sum_1^n E_D(t)} \quad (11)$$

In this case, n represents the 219,000-hour duration of the research. The CO2 emission ECO_2 (t) in time (t) is determined by Equation 13, and the second goal ECO2T is computed using Equation 12.

$$\mathrm{ECO_2T} = \sum_{t=1}^{n} ECO_2(\mathrm{t}) \tag{12}$$

$$ECO_2(\mathrm{t}) = \mathrm{S_{ECO_2}}\left(\frac{\mathrm{kg}}{\mathrm{l}}\right) \times \ \mathrm{F_{cons}}(\mathrm{t})\ (\mathrm{l/h}) \quad . \tag{13}$$

Where: $\mathrm{S_{ECO_2}}$ stands for Specific CO2 emissions in term of liters of fuel and give as (2.7 kg/l), ECO_2(t) CO_2 emission in time (t)(kg)

Using Equation 14, we can meet the optimization requirement of (reliability 100% continuous) for the project's 25-year lifespan by powering the load.

$$ET(t) \geq \frac{E_D(t)}{\mathcal{E}_{inv}} \tag{14}$$

$$E^T(t) = x_1 \times \mathrm{EWT}(t) + x_2 \times \mathrm{EBS}(t) + x_3 \times \mathrm{EDG}(t)\ \times\ \mathcal{E}_{inv} \tag{15}$$

Where: $E^T(t)$ stands for a total energy for HES in time (t), $\mathrm{EWT}(t)$ stands for WT unit energy in time t (Wh), $\mathrm{EBS}(t)$ stands for BS unit energy in time t (Wh), and $\mathrm{EDG}(t)$ DG unit energy in time t (Wh).

Here, the sum method weighing (multi-objective) is used to minimize CT, and ECO_2T by using Equation 16.

$$F(X^i) = \mathrm{CT}(X^i) \times W_1 + \mathrm{ECO_2}T(X^i) \times W_2 \times TC_{CO_2} \tag{16}$$

Where: $F(X^i)$ stands for the function associated between CT, and ECO_2T after transforming it to the same unit ($), by multiplying ECO2T by TC_{CO_2} that stands for tax carbon, in this paper take tax carbon in Sweden's (150 $/ton) since he has a higher tax carbon in a world. Optimal sizing for HES has a minimum $F(X^i)$.

4. Results and analysis

With a total of 75 WT, 322 BS, and 1 large DG, the system configuration is given as X=[75 322 1], with 37 hybrid inverters, as a result of the optimization that minimizes CT and ECO2T while continuously providing the load demand with electricity for 25 years. Figure 5 shows the system's behavior for this design during the first 10 days of August, the month of summer. The performance of the WT-BS-DG system configuration over 25 years is displayed in Table 4.

Table 4. WT-BS-DG system configuration performance for 25 years

Configuration (X)	CT ($)	ECO_2T (kg)	COE ($/kWh)
[75 322 1]	1.604×10^6	3.1565×10^6	0.0913185

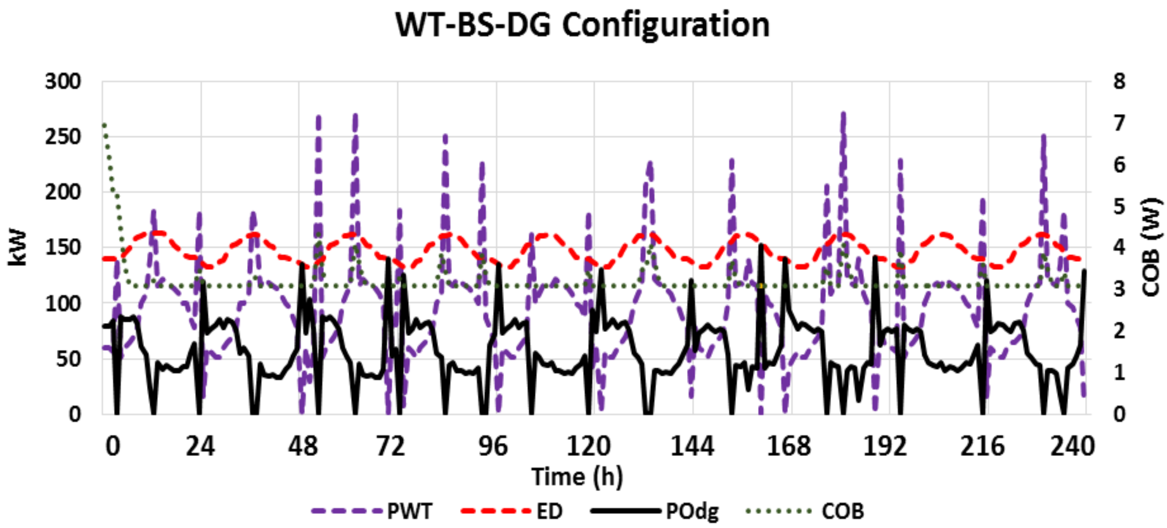

Figure 5. Conduct (WT-BS-DG) system for the initial ten days of August

5. Conclusion

In this research, we apply the GA algorithm to determine the best size of the HES for multi-objective optimization, which includes the WT, BS, and DG. Reducing energy cost (COE) is the primary goal of lowering CT, and minimizing ECO2T is the secondary goal. Continuously meeting the load demand with power throughout the project's 25-year life cycle is the optimization constraint known as reliability. Based on the findings, we can say:

1. The ideal design when combining RESs, BS, and DG yields a minimum objective function Q(X) that links the multi-objective functions CT and ECO2T. The optimal size of the HES is 75 WT, 322 BS, and one large diesel generator.
2. Waveform and electrical load are just two examples of the many kinds of data that the GA algorithm can handle. On top of that, it can keep the power flowing for 25 years while simultaneously lowering objectives.

6. Recommendation

The paper aims to optimize a hybrid energy system (HES) that is built around a mix of renewable and non-renewable energy sources to improve the distribution of power to a local community in Iraq. While trying to reach these goals, optimization should focus on a minimum cost, and CO_2 emissions with high reliability (100%) throughout a 25-year lifespan.

Microstrip antenna incorporated into HES provides several advantages. These antennas provide an excellent communication connection within the system that facilitates the transmission of data and control signals among components. Their minimized and lighter side means space savings in the system, thereby improving the reliability of the communication system by removing the possibility of a broken wireless connection.

Filters are of vital importance in HES since they are responsible for the reduction of sounds and outside sources of interference that often lead to less clean and therefore less effective power signals. They also have the function of regulating and strengthening frequency characteristics, guaranteeing good stereotypicality and upshots. Filters help with signal quality and stability as they reject/eliminate unwanted frequencies and harmonics.

As the power distributors, power dividers are fundamental in the HES operations. These systems facilitate the controlled distribution of power from the diversity of resources to meet the load requirements, and this works well to guarantee the balanced distribution of power to the different components and also improves efficiency and the overall performance of the system. The decentralization of power also enables the scalability of the system which can easily add more solar sources or storage as needed.

Usually, those electronics like microstrip antennas, cloud computing, filters, diplexers, and power dividers are to transmission, energy management, and system performance in the HES. These elements perform a very important function in conditioning a reliable, efficient, and sustainable operation of the hybrid energy system by aiming at emission and cost reduction [52-56].

Conflict of interest

The authors declare that they have no conflict of interest and all of the authors agree to publish this paper under academic ethics.

Author contributions

Faisal Theyab Abed: Conceptualization, methodology, data curation, writing - original draft. Nisreen Khalil Abed: Conceptualization, investigation, visualization, writing - review & editing. Ibtihal Razaq Niama ALRubeei: Methodology, formal analysis, validation, supervision. Aday R. H. Alrikabi: Project administration, funding acquisition, resources.

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