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Optimization of Stand-Alone Renewable Energy Facilities Inside an Academic Premises

Rajendran Joseph Rathish*,[1] and Krishnan Mahadevan*

Abstract – *Energy conservation and carbon-dioxide emissions revamp energy management initiatives in institutions. Renewable energy powered equipment are employed to achieve this task. This paper integrates an energy mixture facility using heuristic techniques for allocating renewable energy facilities to power street lamps installed in academic premises. A case study is done on a college campus to analyze the feasibility of improved Hybrid optimization using genetic algorithm (iHOGA). The iHOGA offers simple steps and provides more allocation plans to satisfy minimum net-present cost (NPC), minimum carbon-dioxide (CO_2) emissions, and minimum unmet load (UL). The results demonstrate that the best solution obtained for solving multi-objective optimization considering three objectives include the exploitation of both solar and wind energy.*

Keywords – *iHOGA, multi-objective, optimization, renewable energy, stand-alone.*

1. INTRODUCTION

Energy is the critical material base for national economic development and people's life. In recent years, the countries globally realize the importance of energy to the human. Conventional energy sources are used to provide energy which has got many constraints. Solar and wind energy are good alternatives to fossil fuels. Power generation locally can be achieved by using these alternatives. Howbeit, intermittent and unpredictable nature of these energy sources, limit their integration into energy markets. Energy storage and backup units are combined to reduce these drawbacks partially. Utilization of more than one source of energy increases complexity.

However, hybrid energy sources are proven to be preferable for the recent power demand without harming the environment. Heuristic techniques are used to find the optimal combination of energy sources. This work reveals the design of a hybrid PV-wind-diesel-battery installation for the generation of electric energy to power street lamps in academic premises Figure 1.

Design of the hybrid system is carried out by minimizing three objectives (cost, pollutant emissions, and unmet load). These three objectives are usually conflicting in nature as one improves at the expense of others [1]. A large number of variables are considered to solve the problems of this kind. Classical optimization techniques consume more time or even fails to find the optimal solution. Heuristic techniques have been used to solve the problems of this kind [2].

Multi-objective evolutionary algorithms (MOEA's) are the most used techniques which are proved to be efficient in solving these problems because of the concept of Pareto Optimality [3]. Figure 2 portrays a set of viable solutions to a multi-objective optimization problem of minimization assessing two objectives (F_1 and F_2). Best non-dominated solutions of the Pareto front are obtained at the end of the optimization problem simultaneously minimizing both objectives. The solution obtained at the end is considered as the "best Pareto front".

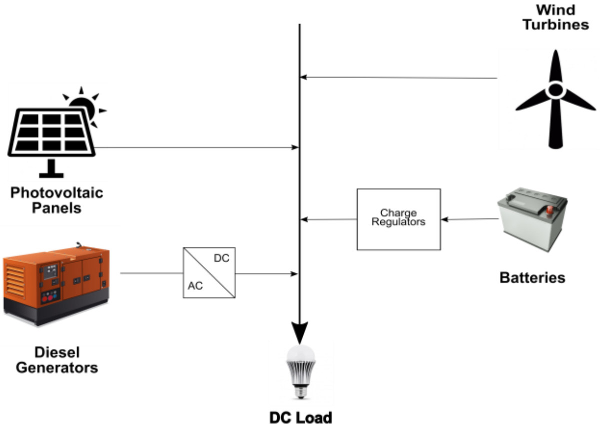

Fig. 1. PV-wind-diesel-battery system.

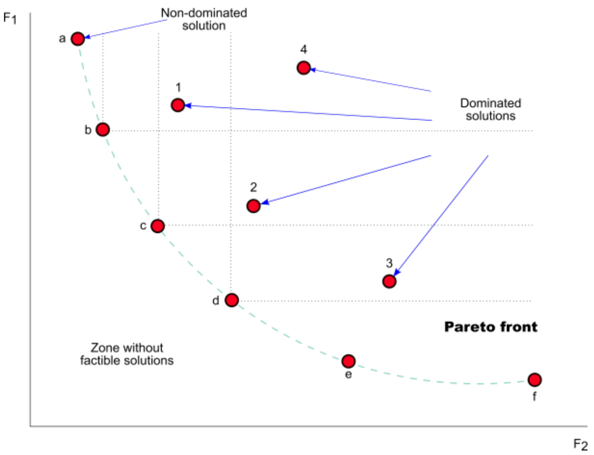

Fig. 2. Pareto front of MOEA.

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Nesamalar [4] reviewed Tamil Nadu's achievement in extracting renewable energy, its initiatives, and policies framed to exploit the natural renewable sources. Keoleian [5] calculated life-cycle energy and CO_2 emissions of a standard house and an energy efficient house for improving CO_2 reduction. Dufo-Lopez [6] discussed the multi-objective design of hybrid systems for different load profiles. Campus building with low energy consumption can notably reduce energy demand and CO_2 emission.

Stand-alone hybrid lighting systems are self-sustaining, economically viable and also it reduces the transmission and distribution losses. Street lighting using LEDs (light emitting diodes) have many credits than using CFL (compact fluorescent lamp) and, Halogen lamps.

This work aims at utilizing a hybrid renewable energy system for powering LED street lamps of academic premises located at Dindigul, Tamil Nadu, India. iHOGA tool is used to optimize the considered objectives to meet the load demand of the street lamps. The hybrid system is inspected and juxtaposed with PV-diesel systems and wind-diesel systems. The results obtained recommend the utilization of PV-wind-diesel-battery system when compared with systems having a single renewable source.

This paper is structured as follows: Section 2 discusses the methodology used for different renewable systems. Section 3 gives details about different objective functions considered. Section 4 describes the algorithms used for solving the multi-objective problem. Section 5 examines the results obtained for the considered system components. Finally, Section 6 concludes the optimal results obtained for the complex multi-objective problem.

2. METHODOLOGY

This section discusses the mathematical models of the components and evaluation of each combination of components along with the control strategy used in the simulation.

2.1 Mathematical Model of Hourly Simulation of the System

The assessment of each combination of components and control strategy hints that the behavior of that combination must be simulated. The simulation is executed in hourly steps, for some years n_Y (not known a priori) till the battery bank's remaining potential drops to 80%. It is assumed that the load, irradiation, and wind speed have the same values for different years. However, the performance of the battery bank is not the same for the different years, as the remaining capacity of the battery bank reduces continuously.

2.1.1 PV generator

The input data could be the radiation on the horizontal surface or the peak sun hours. The tool uses the Rietveld equation [7] to convert the input data into average clearness index for each month of the year and acquires the clearness index for each day of the year. Graham model [8] determines the global hourly irradiation $G_h(t)$. PV inverter includes maximum power point tracking (MPPT). The output power $P_{pv}(t)$ (W) of the generator, during the hour t of the year $(t=0,\ldots,8760)$, is given by Equations 1 and 2.

$$P_{pv}(t) = P_{STC} \times \frac{G_h(t)}{1kWh/m^2} \times \left[1 + \frac{\alpha}{100}\left(T_C(t) - 25\right)\right] \times F_{dirt} \qquad (1)$$

$$T_C(t) = T_a(t) + \left(\frac{NOCT - 20}{0.8}\right) \times \frac{G_{h_{yearY}}(t)}{1kwh/m^2} \qquad (2)$$

2.1.2 Wind generator

The power curves provided by the manufacturing companies are used to compute the current generated by the wind turbines. Wind data read from a file supplies hourly input values for the selected geographical location. Calculation of output power of the wind turbine is similar to the one used in HOMER [9]. The method includes two steps:

- Equation 3 calculates the wind speed at the hub height.

$$V_{hub} = V_{data} \times \frac{\ln\left(\frac{Z_{hub}}{Z_0}\right)}{\ln\left(\frac{Z_{data}}{Z_0}\right)} \qquad (3)$$

- The power curve of the wind turbine calculates the power output.

2.1.3 Diesel generator

The output power of the renewable generators, the load, the control strategy and the state of charge (SOC) of the batteries determines the output of the diesel generator $P_{GEN}(t)$. The diesel fuel consumption l/kWh during the hour t is calculated as follows:

- If the diesel generator was working during the earlier hour:

$$Cons_{fuel}(t) = \left(B \times P_{GEN,rated}\right) + \left(A \times P_{GEN}\right) \qquad (4)$$

- Alternatively:

$$\begin{aligned} Cons_{fuel}(t) = {} & \left(B \times P_{GEN,rated}\right) + \\ & \left(A \times P_{GEN}\right) + \left(F_{START}\left[B + A\right] \times P_{GEN,rated}\right) \end{aligned} \qquad (5)$$

2.1.4 Batteries

The battery output current depends on the output power of the renewable generators, the load, the control strategy, and its SOC. A lifetime of the battery depends on its aging. Simulating the performance of the battery is a complex task to achieve exactly. Most of the hybrid system optimization uses classical battery models. Classical models predict the lifetime too optimistically [10]. This paper uses a weighted Ah-throughput model introduced by Schiffer [11].

2.1.5 Inverter/charger

Pulse width modulation controller with the charge in three stages models the inverter/charger. Usually, the charger efficiency $\mu_{(i/c)}\,charger$ is considered at a fixed value. Howbeit, the inverter efficiency depends on the output power $\mu_{(i/c)}\,inverter$ is as shown in Figure 3.

3. OBJECTIVE FUNCTIONS

The objective functions considered are:

- Minimization of total net present cost: NPC (€).
- Minimization of CO_2 emissions: E ($kg\,/\,year$).
- Minimization of unmet load: UL ($kWh/\,year$).

3.1 Costs

NPC (initial investment plus the deducted present values of all future costs) is the cost throughout the total life of the installation. The life of the system is usually the life of the PV panels. The following section describes the costs considered:

- Purchasing cost of the PV panels, the wind turbine, the batteries, the inverter, the charge regulator, and the diesel generator.
- The maintenance cost of the system components.
- The replacement cost of the components throughout the system life.
- The operation cost of the components.
- Fuel consumption cost throughout the life of the system.

References [12]-[14] describe the overall calculation of the costs.

3.2 Pollutant Emissions

CO_2 emitted per kg represents the amount of pollutant emission. When compared with other sources, burning of fuel emits more pollution which is the primary cause of the greenhouse effect. The total amount of kg of CO_2 produced by the hybrid system throughout 1 year (E) is the correct measure of the pollutant emissions. Characteristics of the diesel generator decide the value of the kg of CO_2 emitted. Usually, this value falls between 2.4 to 2.8 kg/l [15].

3.3 Unmet Load

The unmet load (UL) is the amount of energy not served in 1 year measured in kWh/year. Equation 6 gives the percentage value of the unmet load.

$$UL\ (\%) = \frac{UL\,(kWh/\,year)}{Total\ annual\ electric\ load\ (kWh/\,year)} \tag{6}$$

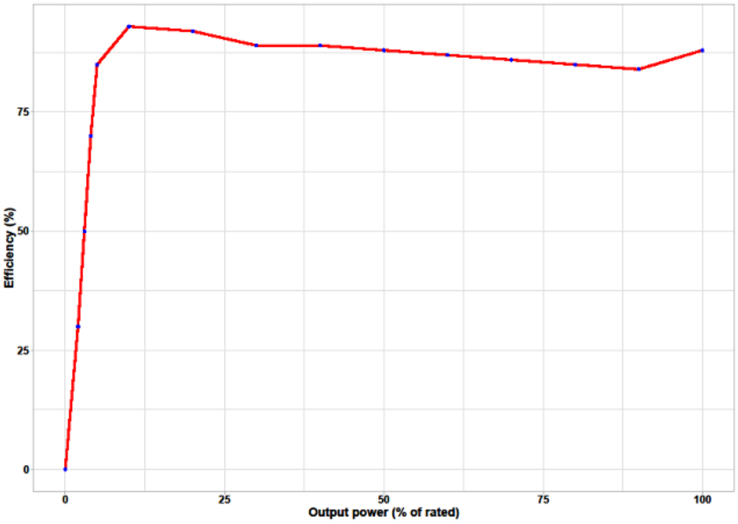

Fig. 3. Inverter efficiency.

4. MULTI-OBJECTIVE OPTIMIZATION EVOLUTIONARY ALGORITHM

The iHOGA uses two different evolutionary algorithms. The main algorithm uses a multi-objective evolutionary algorithm (MOEA) which codifies the components of the system, and a secondary algorithm uses a Genetic algorithm (GA) which codifies the control strategy. The secondary algorithm runs to find the best control strategy (lowest NPC) for the combination of components given by the main algorithm.

5. COMPUTATIONAL RESULTS: MULTI-OBJECTIVE OPTIMIZATION OF A HYBRID SYSTEM.

Following the methods discussed in Section 2, as an example, it is shown the optimization of PV-wind-diesel-battery system considering the objectives discussed in Section 3 to supply lighting for the streets of academic premises. The lights illuminate the streets for 12 hours from 6 pm to 6 am. Each light has a separation distance of 35 m. 35 LED lights are needed to cover a distance of 1225 m with 40 W each. The load profile for street lighting is around 1400 W, shown in Figure 4.

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The considered academic premises is located at Dindigul.

- PSNA College of Engineering and Technology (latitude 10.41° N, longitude 77.90º E): Monthly average irradiation over a horizontal surface from NASA web [16], annual average 4.975 kWh/m^2/day Figure 5. Hourly wind speed yielded from NASA web [16], annual average wind speed of 3.4 m/s Figure 6.

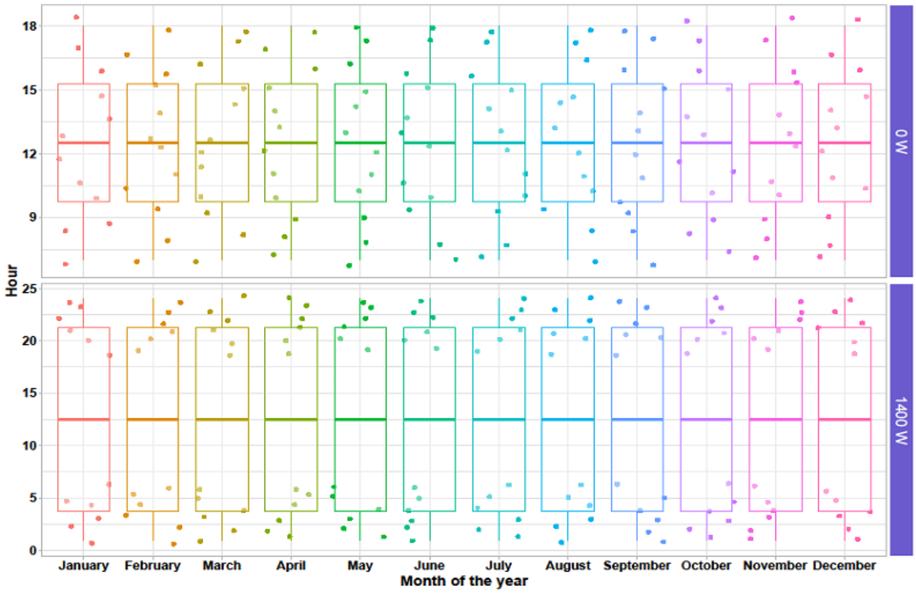

Fig. 4. Load profile (DC only).

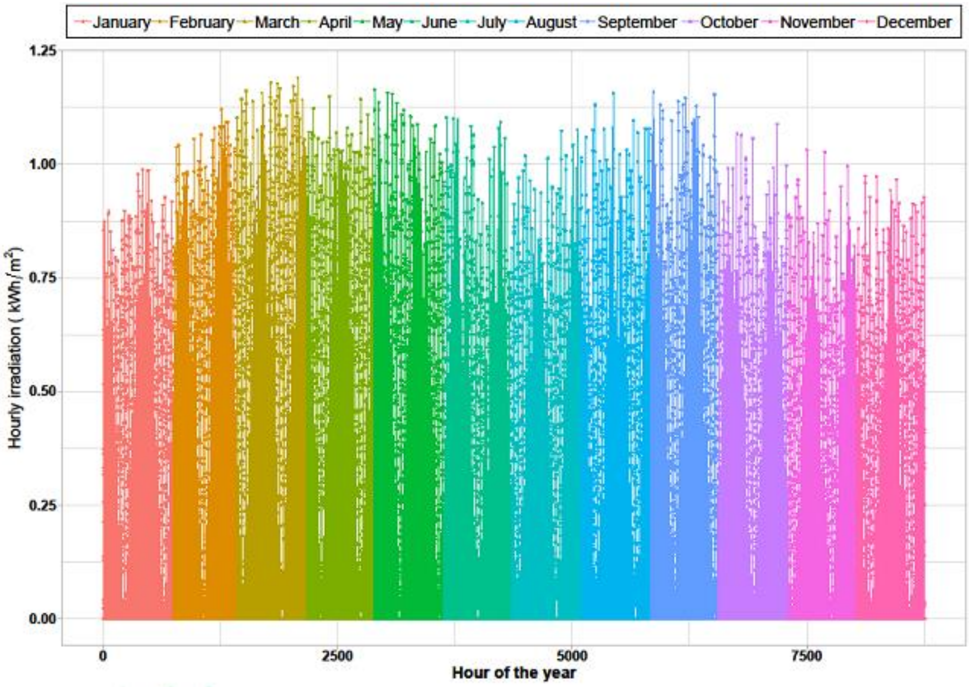

Fig. 5. Solar irradiation.

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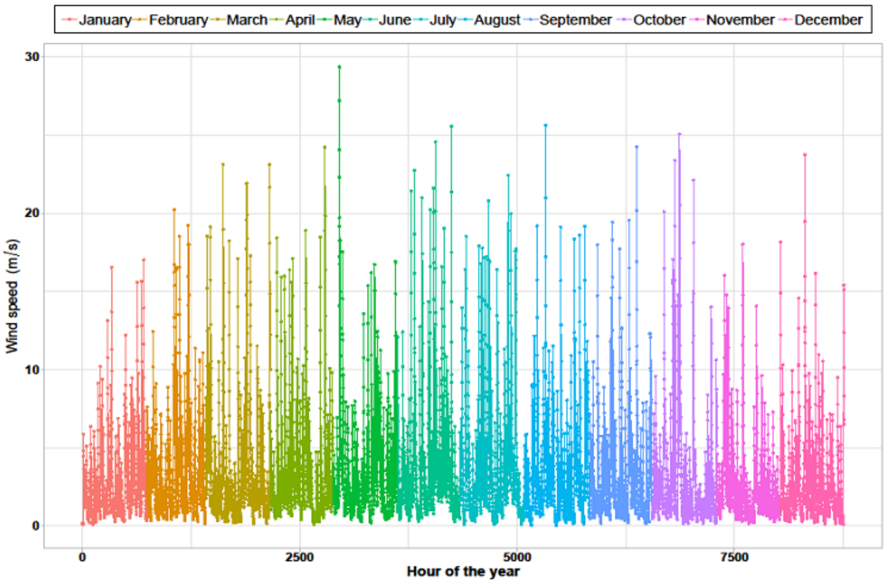

Fig. 6. Wind speed.

5.1 PV Panels

PV panels have a lifespan of 25 years and have a loss factor of 1.2. Table 1 shows the six types of PV panels considered in the design. The system includes any one of these PV panel types.

5.2. Wind Turbines

There are five types of wind turbines, shown in Table 2. The studied location is at the height of 268 m above the sea level which has surface roughness class 1.5. All the wind turbines have a lifespan of 15 years. Annual inflation rate accounts to -4% and the envisaged limit of variation of the wind turbine costs is -20%.

5.3. Batteries

Table 3 presents the five types of battery banks. The manufacturer recommends the minimum state of charge (SOC_{min}) as 2%. It has a floating life of 18 years, the monthly self-discharging coefficient of 3%, round-trip efficiency of 85%, an annual inflation rate of -2% and a maximum limit of variation of -60%.

5.4 Diesel Generators

Five possible types of diesel generators have been considered as listed in Table 4. It has a fuel price of 0.83 €/litre with 5% inflation rate. All the diesel generators have similar fuel consumption parameters: A = 0.2461(l/kWh) and B = 0.08145 (l/kWh) [17]. The manufacturer recommends a minimum output power of 30% and has an expected lifespan of 10000 hours for all the generators.

5.5. Inverters

Table 5 lists the considered four types of inverters. It has a lifespan of 10 years. The output power decides the efficiency (maximum efficiency of 93% at 10% output power).

Table 1. PV generators considered.

Type	Nominal voltage (V)	Short-cut current (A)	Peak power of the PV generator (W_p)	Acquisition cost (€)
0	0	0	0	0
1	24	4.86	150	320
2	24	5.46	190	238
3	12	6.79	100	110
4	12	8.33	130	335
5	12	8.73	135	247

Table 2. Wind turbines considered.

Type	Maximum output power (W)	Acquisition cost (€)	O and M cost (€ /year)
1	925	2865	85
2	660	4255	85
3	1660	4875	98
4	3471	7555	151
5	3260	9700	195

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Table 3. Battery banks considered.

Type	The capacity of the battery bank (Ah)	Maximum current (A)	Round trip efficiency (%)	O and M cost (€ /year)	Acquisition cost (€)
1	550	110	20	2.02	202
2	816	163.2	20	2.98	298
3	1340	268	20	4.12	412
4	1940	388	20	5.78	578
5	2240	448	20	6.64	664

Table 4. Diesel AC generators considered.

Type	Rated output power (kVA)	O and M cost (€ /hour)	Acquisition cost (€)
0	0	0	0
1	1.9	0.14	800
2	3	0.17	1050
3	4	0.18	1200
4	5.5	0.22	1300

Table 5. Inverters considered.

Type	Nominal power (kVA)	Maximum DC charging current (A)	Acquisition cost (€)
1	4	96	2400
2	6	131	3200
3	8	192	4800
4	12	288	7200

5.6 Charge Regulators and Rectifiers

Consider four charge controllers with maximum power point tracking. It has an acquisition cost of 30 € +$(7 \times I)$ €, where I is the maximum input current and has a lifespan of 10 years. Each combination of the components calculates the rectifier size. It has an acquisition cost of 100 €+$(200 \times p)$ €, where p represents the rated output power in kW.

5.7 Results

The load profile considered is analyzed under three cases:

1. PV-battery-diesel (SBD) system.
2. Wind-battery-diesel (WBD) system.
3. PV-battery-wind-diesel (SBWD) system.

Several executions have been carried out for all the three cases to find the optimal solutions for the considered objective functions. Figure 7 unveils progress of the best Pareto front for all the three cases. Table 6 shows the details of the best solution of the Pareto optimal set identified in Figure 7. The NPC is the lowest in SBWD system. Figure 8 depicts the percentage share of energy cost for the best optimal set for all the three cases.

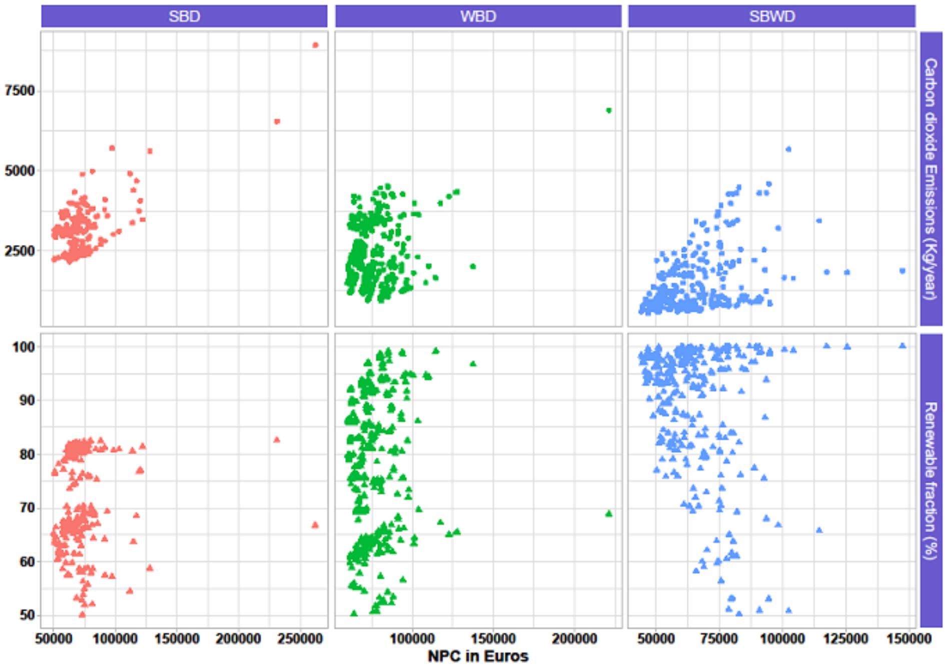

Fig. 7. Pareto front evolutions.

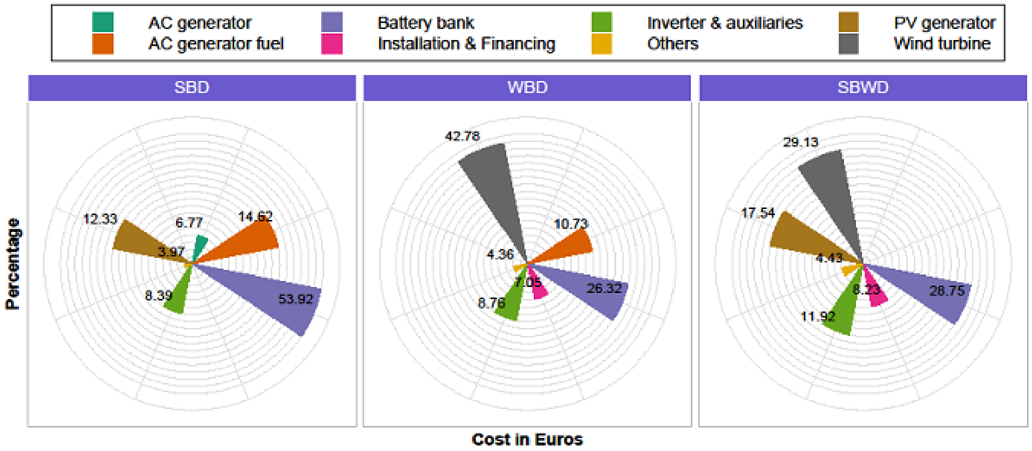

Fig. 8. Share of energy cost.

Figures 9 to 11 show the outputs of the three energy sources along with the production of excess energy. In all the three cases, energy production is excess. Figure 12 presents the energy utilization for the best Pareto front.

Table 6. Pareto set.

System parameters	SBD	WBD	SBWD
PV panel	Type 2	-	Type 2
Peak power of the PV generator (kWp)	4.56	-	4.56
Slope (°)	10	-	20
Battery bank	Type 1	Type 2	Type 1
The nominal capacity of the battery bank (kWh)	26.4	39.1	26.4
Days of autonomous	1.2	1.7	1.2
Wind turbine	-	Type 4	Type 4
Diesel generator	Type 1	Type 2	Type 2
Inverter	Type 1	Type 1	Type 1
Control strategy	Cycle charging	Cycle charging	Cycle charging
Hours of AC generator operation (hour/year)	939	417.84	48.16
Batteries replacement cycle (year)	2.16	9.01	7.46
Renewable fraction (%)	80.6	86.4	98.4
Unmet load (%)	0	0	0
CO_2 emissions (kg CO_2/year)	2234	1482	584
Total net present cost of the system (€)	62747.9	60083	44122
LCE (€ /kWh)	0.41	0.39	0.29

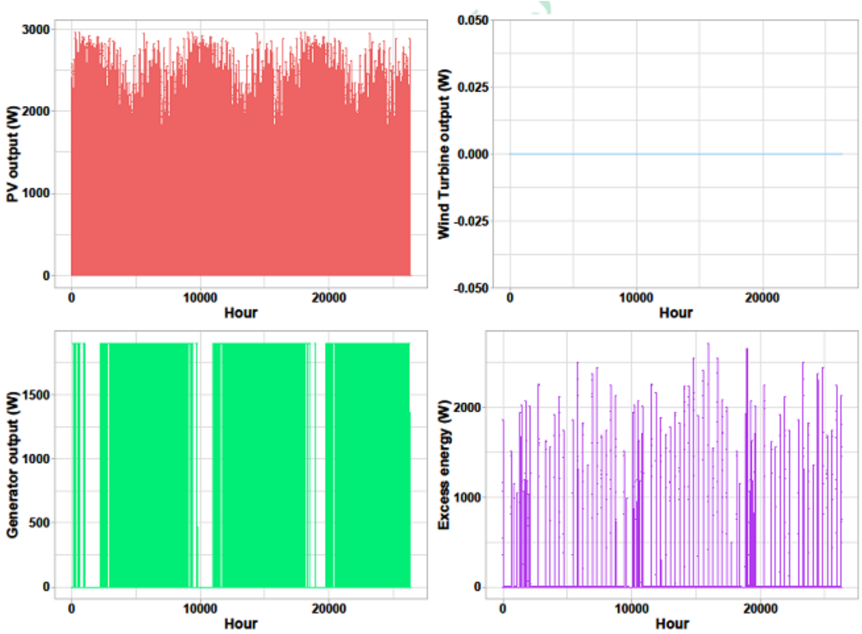

Fig. 9. Solar–battery–diesel system outputs.

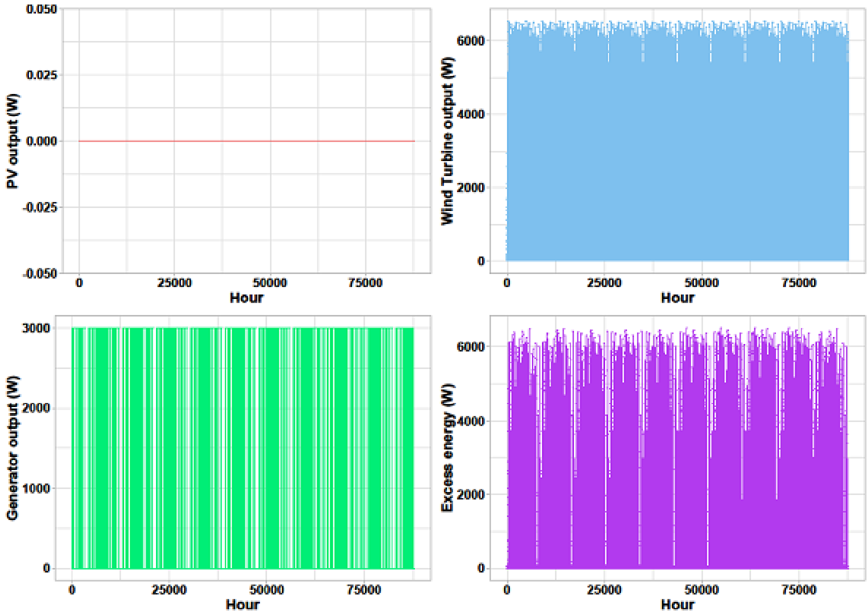

Fig. 10. Wind–battery–diesel system outputs.

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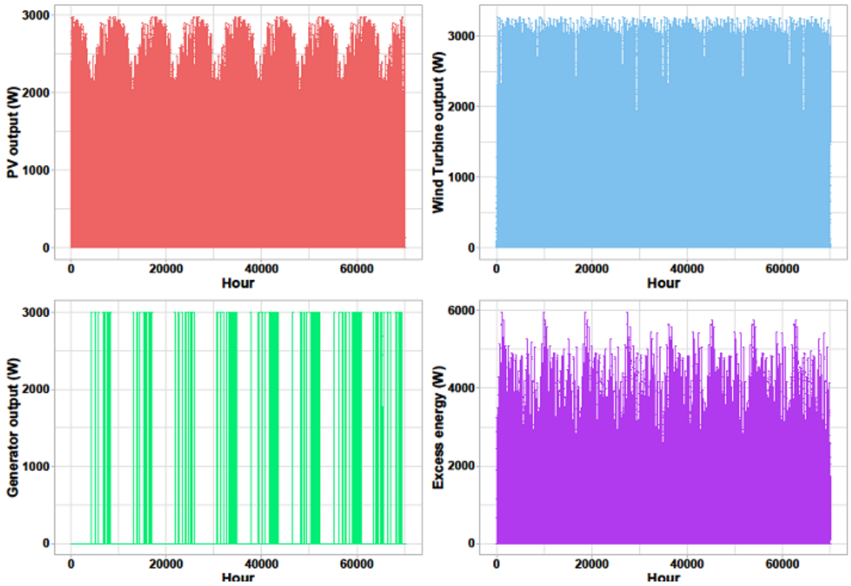

Fig. 11. Solar–battery–wind–diesel system outputs.

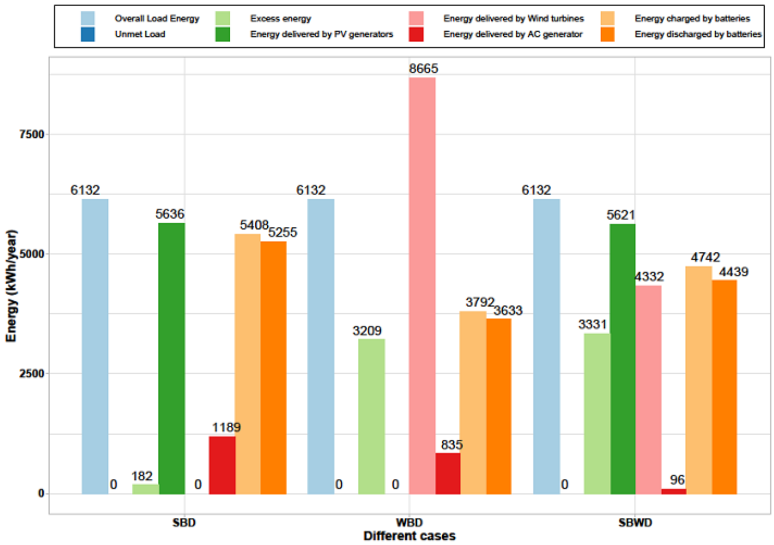

Fig. 12. Energy utilization for the best Pareto front.

6. CONCLUSIONS

In this paper, for the first time, iHOGA has been used and applied to the multi-objective design of a hybrid system for electrical generation to power street lights of academic premises minimizing simultaneously three objectives: NPC, CO_2 emissions, and UL. For the complex design problem, heuristic techniques have been used to find the best optimal solution for three different combinations (SBD, WBD, SBWD) of the hybrid systems. Schiffer battery model used in the design predicts the battery life-time more accurately. It is recommended to use both solar and wind energy to meet the required load demand.

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NOMENCLATURE

α	Power temperature coefficient (%/°C).
A	Coefficient of the consumption curve (l/kWh).
B	Coefficient of the consumption curve (l/kWh).
$Cons_{fuel}$	Fuel consumed (liters).
F_{dirt}	Factor to consider the losses due to dirt, wires, module mismatch or power tolerance and other losses.
F_{Start}	Factor to consider the extra fuel due to the start of the generator.
$G_h(t)$	Radiation (kWh/m^2) over the tilted surface over the tilted surface of the PV panels during the hour t .
l	liters.
LCE	Levelized cost of energy
$NOCT$	Nominal operation cell temperature (°C).
O and M	Operation and Maintenance.
$P1_{generator}$	The intersection point of the cost of

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	supplying energy with the batteries and the cost of supplying energy with the AC generator (W).
$Pgenerator_{\min}$	Minimum operational power of the generator (W).
$P_{(GEN,rated)}$	Generator rated power (kWh).
P_{STC}	Output power in standard test conditions.
$SOC_{minimum}$	Minimum SOC of the battery bank
$SOC(stp_{generator})$	SOC set point of the batteries.
$T_a(t)$	Ambient temperature (◦C).
$T_c(t)$	PV cell temperature (°C).
V_{data}	Wind speed at anemometer height (m/s).
V_{hub}	Wind speed at the wind turbine hub height (m/s).
W	Watts.
Z_0	Surface roughness length (m).
Z_{data}	Anemometer height (m).
Z_{hub}	Hub height of the wind turbine (m).

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