# Optimal Sizing of Grid-Connected Hybrid Renewable Energy System Using the GWO Algorithm and Adapting the Time-of-Use Tariff Rates

**Joshi Sukhdev Nirbheram, Aeidapu Mahesh, and Ambati Bhimaraju**

**Abstract** The use of renewable resources like solar and wind has been encouraged by the depletion of conventional fuels and global warming since they are friendly to the environment. Combining these resources with battery storage can produce clean, affordable, and dependable energy. This paper presents the optimization of the solar photovoltaic (PV)-wind turbine (WT)-battery using the gray wolf optimization (GWO) to optimize the levelized cost of energy (LCE). To obtain the operational benefits of the hybrid renewable energy system (HRES), limit the use of gird power, maximize the renewable use of renewable sources, and limit the surplus Energy of the HRES, the restrictions are the power import rate from grid (PIRG) and the Excess energy rate of renewable (EERR). A novel approach to energy management is suggested, offering a variable rate for grid electricity purchases that adapts the Time-of-Use (TOU) price. The variable tariff from the grid enhances the capability and stability of the HRES. The energy management system (EMS) considers the higher cost of the grid when the burden on the grid is more and vice versa. The EMS also balances energy between renewable sources, batteries, and Demand. The proposed study has been investigated in the location of the Kanyakumari district, India.

**Keywords** Hybrid renewable energy systems · Energy management system · Levelized cost of energy

## 1 Introduction

In today's world, replacing fossil fuels with renewable sources is critical considering climate change [1]. But, the uncertain and sporadic nature of renewable sources causes an unreliable power supply to the load. The combination of two and more renewable sources is used to improve reliability, like solar PV, WT, bio-gas, etc.

J. S. Nirbheram (✉) · A. Mahesh · A. Bhimaraju
Sardar Vallabhbhai National Institute of Technology Surat, Surat, Gujarat, India
e-mail: sukhdevjoshi58@gmail.com



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Solar PV gives the maximum power during the day, whereas WT gives the most power at night. So, Due to the complementary nature of solar PV, WT is the best choice for renewable sources [2]. But, a backup storage system is essential whenever the renewables are unavailable to supply the load [3]. The battery storage has a distinct advantage over other storage due to its high specific energy, prolonged storage durations, and quick response. Hence, solar PV, WT, and battery storage are the best configuration for the HRES to fulfill demand [4]. The Ref. [5] presented the optimal sizing of HRES with the solar PV, WT, and battery storage configuration.

However, energy management system is crucial in HRES to minimize the system operating cost and optimal dispatch of renewable sources. The EMS of HRES is a difficult task considering the uncertainty of renewable sources and load power [6]. Ref. [7] EMS is used for the load scheduling to minimize the energy cost and maximize the system's savings. The solar PV-WT-battery hybrid renewable system presents excess power from renewables charging the battery. If the renewables are insufficient to supply the load, grid power supplies the deficit power [8]. In this paper, the EMS offers a variable tariff to increase the stability of the grid and provides economic benefits to the customer. The TOU is used to demonstrate the variable tariff of the gird [9].

As a result, the literature reviewed above concluded that the EMS is crucial to the HRES's ideal size. Therefore, this study suggested a revolutionary energy market system (EMS) that offers a variable pricing for buying and selling energy. Additionally, the Gray Wolf Optimization (GWO)-efficient metaheuristic technique is employed to determine the HRES's ideal size. The paper's key contribution is listed below:

- The optimal sizing of the solar PV, WT, and battery has been performed with the objective function of LCE subjected to constraint PIRG and EERR. The constraint PIRG encourages the system to limit the power from utility. At the same time, the EERR limits the over sizing of renewable sizing, which will help in the overall cost reduction of the system.
- The TOU tariff rates are used to exchange power between the grid and HRES. The load is divided into peak, off-peak, and valley, so different tariffs are entitled to different periods.

## 2 Modeling of HRES Components

### *2.1 Modeling of Wind Turbine*

Measure the wind speed in the designated region for an hour and compare it to the cut-out speed ($u_{cout}$), cut-in speed ($u_{cin}$), wind speed at turbine altitude ($u$), and rated speed ($u_r$) to get the average wind power. The following is how the wind turbine's output power is expressed [10]:

$$P_{wt} = \begin{cases} 0, & when, u < u_{cin} \\ P_{wtr} \times (\frac{u^3 - u_{cin}^3}{u_{cr}^3 - u_{cin}^3}), & when, u_{cin} \leq u \leq u_r \\ p_{wtr} & when, u_r < u < u_{cout} \\ 0, & whenu \geq u_{cout} \end{cases} \quad (1)$$

## 2.2 Modeling of Solar PV

In [11], the solar irradiance, absorption capability, cell temperature, and panel area are all connected to the output power of the PV system $Ppv(t)$.

$$P_{pv}(i) = \frac{I(i)}{1000} \times P_{pvr} \times \eta_{pv} \times f_{dr}[1 - \alpha_T(T_c - T_{c,STC})] \quad (2)$$

where $I$ is Irradaition in $(w/m^2)$, $P_{pvr}$ is rated power in $(kW)$, $\eta_{pv}$ is efficiency, $f_{dr}$ is a derating factor of solar PV, $\alpha_T$ is temperature co-efficient, $T_c$ is Cell temperature, and $T_{(c,STC)}$ is temperature at standard test conditions.

## 2.3 Battery Modeling

The battery is in charging or discharging mode, depending on the available renewable energy. When renewable energy is more than the load demand, the surplus power is used to charge the battery. The instantaneous state of charge $SOC(t)$ during the charging process must be determined using the SOC modeling of the battery [12].

$$SOC_{t+1} = SOC_t + \frac{\eta_{charging}(t) \times I_{battery}(t) \times \Delta t}{C(t)} \quad (3)$$

where $I_{battery}$ is the charging current, $\eta_{charging}$ is charging efficiency, and $C(t)$ is the capacity of the battery.

Similar to the charging process, the discharging process of the system is given below:

$$SOC_{t+1} = SOC_t - \frac{\eta_{discharging}(t) \times I_{battery}(t) \times \Delta t}{C(t)} \quad (4)$$

# 3 Objective Function Formulation for Optimization

## 3.1 Total Cost of HRES

The overall cost of the system covers a number of charges, including the cost of the initial investment ($Cost_{in}$), the cost of operation and maintenance ($Cost_{om}$), and the cost of replacement ($Cost_{rep}$) [13].

$$Cost_{total} = Cost_{in} + Cost_{om} + Cost_{rep} \tag{5}$$

## 3.2 Levelized Cost of Energy (LCE)

The LCE is the per unit cost of the HRES and is defined as the cost of the power delivered by the system. The LCE is the ratio of total cost of the HRES to the total energy delivered to load.

$$LCE = \frac{Cost_{total}(\$)}{Energy_{total}(kwh)} \tag{6}$$

where $Cost_{total}$ denotes the total cost of the HRES and $Energy_{total}$ denotes the overall amount of energy supplied by the HRES.

## 3.3 Objective Function

The main objective function of the HRES is to minimize the LCE considering the constraint and limitations. So, the HRES has the main aim of providing the design of the system with minimal LCE [14].

$$minf = minimize(LCE) \tag{7}$$

subject to constraints of grid-connected system

$$\begin{cases} 0 \le PIRG \le PIRG_{max}, & PIRG_{max} = 15\% \\ 0 \le EERR \le EERR_{max}, & EERR_{max} = 10\% \end{cases} \tag{8}$$

The ratio of total power acquired from the grid to the total load demand is known as the power import rate from grid.

$$PIRG = \frac{P_{gridpurchased}}{Load_{Total}} \tag{9}$$

The ratio of excess renewable energy generation to total renewable energy generation is known as the excess energy rate from renewables.

$$EERR = \frac{P_{PV} + P_{WT} - Load_{total}}{P_{PV} + P_{WT}} \quad (10)$$

where $P_{PV}$, $P_{WT}$, $Load_{total}$, are the generation from solar PV, WT, and total load of the HRES.

## 4 Energy Management System

The energy management system is an essential part of the HRES in order to balance the energy balance between renewable sources and the load. The novel EMS is offering the variable tariff and reducing the burden from the gird. The grid offering the high cost while the burden on the grid is more and gird offering the less cost while the burden on the gird is less. The EMS is divided into many parts based on the charging and discharging of the battery.

- In the first mode, when the renewable sources are more than the load and battery SOC is more than 0.8, the surplus power from the renewables supply to the grid at a variable tariff.
- In the second mode, when the renewable sources are more than the load and battery SOC is less than 0.8, the surplus power from the renewables supplies the battery to charge the battery.
- In the third mode of operation, when the renewable sources are less than the load and the battery SOC is greater than 0.2, the battery supplies the deficit power of the load.
- In the last mode of operation, when the renewable sources are less than the load and the battery SOC is less than 0.2, the deficit power of the load is supplied by the grid at a variable tariff (Fig. 1).

## 5 Optimization Techniques

Metaheuristic algorithmic techniques for sizing have been taken into consideration in this research. This study examined scaling methods for the configured system using metaheuristic algorithms. There are many other metaheuristic techniques, but GWO has received the most attention for optimization because of its accuracy in identifying the best optimal solution.

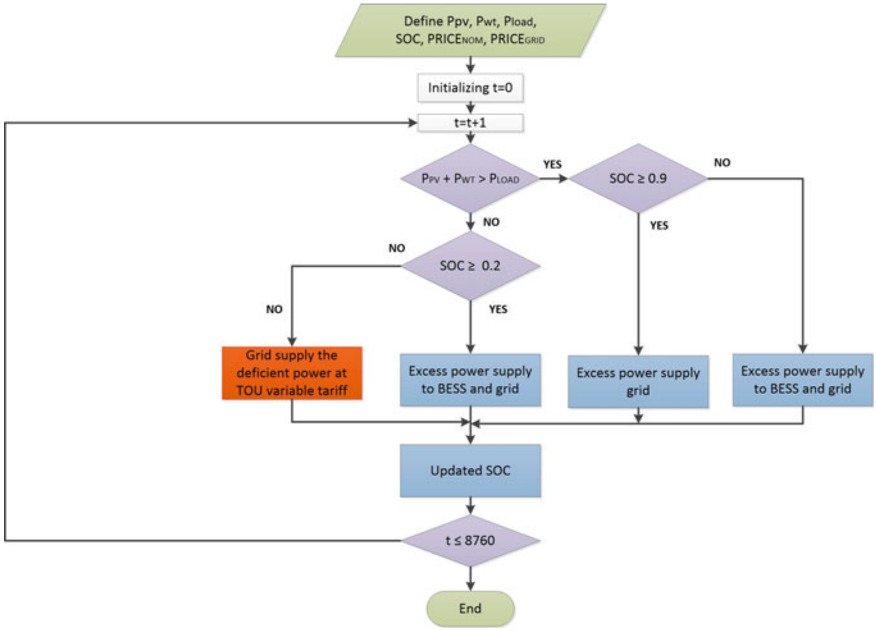



**Fig. 1** Energy management system

## *5.1 Gray Wolf Optimization*

One of the most current metaheuristics swarms intelligence algorithms is the GWO. Due to its superiority over other swarm intelligence approaches, it has been widely customized for a wide range of optimization issues. This section presents the mathematical modeling of the GWO. The first step of the GWO is to chase and encircle, and the proposed equation is given below [15]:

$$Y(t+1) = Y(t) - B \times S \tag{11}$$

where $Y(t+1)$, $Y(t)$ are the gray wolf's next location and current location, respectively. $B$ and $S$ are the coefficients of the matrix, and the vector depends on the prey location $(Y_p)$ and is calculated by

$$S = |C \times Y_p(t) - Y(t)| \tag{12}$$

where $C = 2 \times r_2$ and $r_2$ is the randomly generated vector from [0,1].

Using the aforementioned equations, a wolf may migrate to any place in a hypersphere surrounding the prey. However, this is insufficient to approximate gray wolf social intelligence. As previously stated, social hierarchy is important in hunting and group survival. The finest options for simulating social hierarchy are alpha, beta, and delta. Although there may be more than one wolf in each group in nature, in GWO, it is assumed that there is only one solution for each class for the purpose of simplicity. The three best answers thus far are always presumed to be alpha, beta, and delta in GWO. Due to the fact that alpha, beta, and delta are the top solutions in the population, it has been claimed that they have a solid understanding of where the global optimum of optimization problems is located. Other wolves should be required to update their places in the manner described below:

$$Y(t+1) = \frac{Y_1 + Y_2 + Y_3}{3} \tag{13}$$

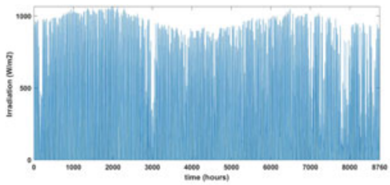
where $Y_1$, $Y_2$, $Y_3$ is calculated using the below equation:

$$\begin{cases} Y_1 = Y_\alpha(t) - B_1 \times S_\alpha \\ Y_2 = Y_\beta(t) - B_2 \times S_\beta \\ Y_3 = Y_\delta(t) - B_3 \times S_\delta \end{cases} \tag{14}$$

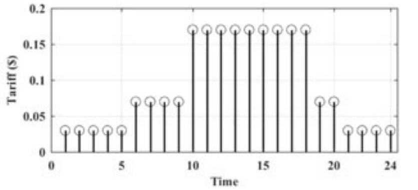
## 6 Results and Discussion

The optimal sizing of the HRES is performed at the specific site location (https://www.sciencedirect.com/science/article/pii/S2352152X22007873). Figure 2a–c demonstrates the solar radiation, wind speed, and load for 1 year. The PV-wind and battery configuration are considered for optimal sizing using the gray wolf optimization algorithm. The variable grid tariff of this study takes into account the TOU pricing in addition to optimal size. To limit the power taken from the grid and increase the use of the renewable power, import rate from the grid (PIRG) and excess energy rate from renewables (EERR) are utilized. To prevent deterioration, the maximum and minimum states of charge of the battery are regarded as 0.8 and 0.2, respectively. Now, to make the comparison of the results of the optimization of the HRES is performed with TOU tariff rates. In TOU tariff rates, the rates are divided into three parts as per the burden on the grid. When the burden on the grid is more, the tariff is more and period is known as peak period. On the other hand, if the burden on the grid is less, the cost of the grid is less and the period is known as valley. On a similar line if the load is in between the peak and valley the period is known as off-peak. The tariff for selling and purchasing is decided based on load demand and as per the TOU tariff, the load is divided into three parts (1) valley, (2) off-peak, and (3) Peak, and the tariff rates for the time periods are 0.03, 0.07, and 0.17, respectively [9].

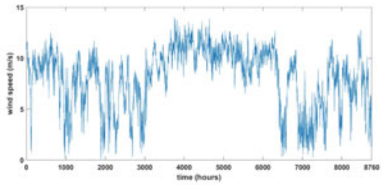
For the comparison, the optimal sizing is performed with different algorithms like the sine cosine algorithm (SCA), Seagull optimization algorithm (SOA), and gray wolf optimization (GWO). The maximum number of iterations is 100, and the population size is 50 considered for the algorithm. The results demonstrated that GWO is giving the best optimum result among the given algorithm. Table 1 shows



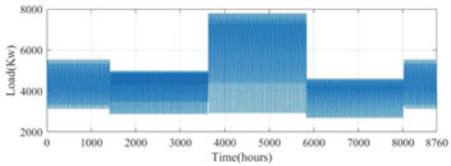

(a) Solar Irradiation with one hour resolution over a year




(b) TOU variable tariff for grid exchange




(c) Wind speed with 1-hour resolution over a year




(d) Seasonal load profile for one year

**Fig. 2** Meteorological data

**Table 1** Optimization results for the constant grid tariff

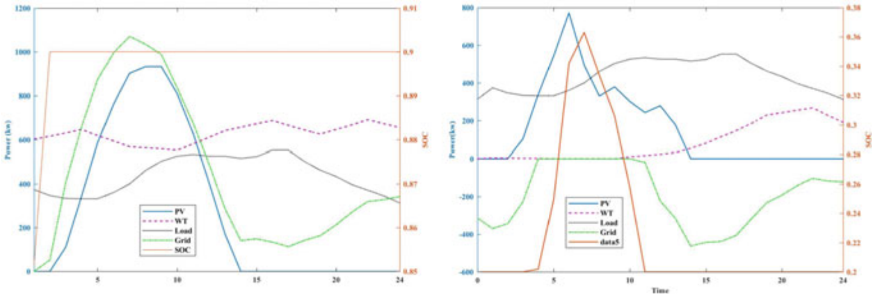
| Optimization algorithm | $N_{PV}$ | $N_{WT}$ | $N_{battery}$ | $LCE$ | $PIRG$ | $EERR$ |
|---|---|---|---|---|---|---|
| GWO | 2976 | 151 | 1882 | 0.1731 | 0.15 | 0.1 |
| SCA | 2965 | 157 | 1855 | 0.1901 | 0.1498 | 0.09 |
| SOA | 2970 | 154 | 1871 | 0.1822 | 0.1499 | 0.1 |

**Table 2** Optimization results for the variable grid tariff

| Optimization algorithm | $N_{PV}$ | $N_{WT}$ | $N_{battery}$ | $LCE$ | $PIRG$ | $EERR$ |
|---|---|---|---|---|---|---|
| GWO | 2952 | 152 | 1884 | 0.1584 | 0.15 | 0.1 |
| SCA | 2960 | 156 | 1869 | 0.1712 | 0.1499 | 0.09 |
| SOA | 2967 | 154 | 1875 | 0.1752 | 0.1499 | 0.1 |

results at constant tariff with a selling tariff of 0.07 and purchasing tariff of 0.17. The optimal result is $N_{PV}$ = 2976, $N_{WT}$ = 151, $N_{bat}$ = 1882 and $LCE$ = 0.1713.

As you can observe from Table 2, the optimal sizing of the HRES considering the variable tariff is demonstrated. The results demonstrate a significant reduction in the LCE. In this case, the GWO optimization gives the best optimum result among the all optimizations given. The optimal results obtained by GWO are $N_{PV}$ = 2952, $N_{WT}$ =152, $N_{bat}$ = 1884, and $LCE$ = 0.1584. Figure 2 shows the power generated by PV and wind, along with that of the SOC of battery, grid power exchange load. The load compensation of the HRES by the renewable sources is demonstrated in Fig. 3.




(a) Compensation of load by renewable sources on day-1

(b) Compensation of load by renewable sources on day-6

**Fig. 3** Compensation of load by renewable sources

Figure 3a shows that from the hours 0:00 to 1:00, the PV is not sufficiently available. However, excess wind power is available, which supplies the load, and surplus power charges the batteries. From hours 2:00 to 8:00, the excess power is available in both the PV and WT, and the surplus power is supplied to the grid. From hours 14:00 to 24:00, the PV power is unavailable to supply the load. However, the excess WT power is available to supply the load, and the surplus is supplied to the grid. In the same way, Fig. 3b shows the compensation of the load by the various sources. From hours 0:00 to 3:00, neither PV nor WT is available to supply the load. However, the deficit power is supplied by the grid. From hours 4:00 to 6:00, excess PV power is available, which meets the load and charges the battery. From hours 7:00 to 11:00, the PV power is less than the load demand, and the WT power is still zero. However, the battery, along with PV, meets the load.

## 7 Conclusion

This study demonstrated the techno-economic analysis of the PV, wind, and battery HRES. The location considered for the research has an ample amount of irradiation, and the wind is available. The findings of the comparison demonstrate a considerable decrease in the LCE, and the proposed EMS offers a variable price for the buying and selling of energy. The cost reduction achieved by using the variable tariff is around 7.5% per year. In the optimal sizing of the HRES, the comparison is made between the metaheuristic techniques like GWO, SC, and SOA. It found that GWO is giving the best optimum results compared to other algorithms. The optimal results obtained by GWO are $N_{PV}$ = 2952, $N_{WT}$ =152, $N_{bat}$ = 1884, and $LCE$ = 0.1584. This study is helpful in the design of the distribution system, economic analysis of the system, and various other parts of the power system.

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