Economic Optimization of Combination of Wind, Solar, and Battery Storage for Grid-Independent Power Supply using Cuckoo Optimization Algorithm

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ABSTRACT:
Renewable energy sources, such as wind and solar, are becoming increasingly popular due to their environmentally friendly and sustainable nature. However, one major challenge associated with these systems is their intermittent nature, which makes it difficult to rely on them as a consistent source of energy. To address this challenge, researchers have developed a combined system that incorporates wind and solar resources with a battery as a storage device, which can provide a sample load pattern independent of the grid. The primary objective of this system is to determine the optimal economic combination of these resources, which can ensure a reliable and consistent supply of electricity. To achieve this objective, the Cuckoo Optimization Algorithm (COA), a metaheuristic optimization algorithm, has been used to optimize the system. The objective function has been implemented in accordance with the constraints, and the results provide insight into the optimal combination of resources. This paper provides a comprehensive analysis of the design and optimization of a wind-solar hybrid energy system with battery storage, using the COA, as well as the results of this analysis. The outcomes indicated that the optimal hybrid system model may be able to reduce system costs by 10–25%. This research's findings can be used to inform the design of sustainable and dependable renewable energy systems.

KEYWORDS: Renewable Energy Source, Wind Turbine; Solar Energy, Cuckoo Optimization Algorithm.

1. INTRODUCTION

The growing demand for renewable energy sources has spurred the development of numerous technologies to harness energy from wind and solar sources [1]–[4]. However, integrating these intermittent and variable renewable energy sources into the power grid presents a challenge [5]–[7]. In order to overcome this obstacle, energy storage technologies such as battery storage have been implemented to ensure a stable energy supply to the grid [8]–[11].

In recent years, the economic combination of wind, solar, and battery storage systems for grid-independent power generation has been intensively researched [12]–[15]. Optimizing such systems can result in substantial

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cost savings while ensuring a reliable energy supply [16], [17]. This article examines the application of the Cuckoo Optimization Algorithm (COA) to optimize the economic combination of wind, solar, and battery storage systems for grid-independent power supply.

The COA is a nature-inspired optimization algorithm based on the behavior of cuckoo birds during reproduction [18]. It is a metaheuristic and stochastic algorithm that has been successfully applied to a variety of optimization issues. In this paper, the COA is used to optimize the economic combination of wind, solar, and battery storage systems for grid-independent electricity generation.

Krishan and Suhag [19] discuss the optimal sizing and techno-economic analysis of a PV–wind–battery hybrid energy system connected to the power grid. The authors use the HOMER software to determine the optimal system size, taking the available renewable energy resources and energy demand into account. The document also contains an economic analysis of the system, which includes the levelized cost of energy and payback period.

Olatomiwa et al. [20] present a methodology for optimally sizing a Nigerian telecom tower in a remote location. The authors use the HOMER software to determine the optimal sizing of the system, taking into account the energy demand and the available renewable energy resources, by taking into account the energy demand. The analysis includes the system's net present cost, levelized energy cost, and payback period.

Using a particle swarm optimization algorithm, Mohamed et al. [21] discussed the optimal sizing and techno-economic analysis of a stand-alone hybrid renewable energy system. The authors use the HOMER, INSEL, TRNSYS, and RETScreen software to determine the optimal sizing of the system, taking the energy demand and available renewable energy resources into account. The document also contains an economic analysis of the system, which includes the levelized cost of energy and payback period.

Using the COA, Sanajaoba and Fernandez [22] present an optimal sizing method for stand-alone hybrid renewable energy systems. The analysis includes the net present cost and the levelized cost of energy.

This study discusses the design of a combined system that utilizes wind and solar resources, along with a battery storage device, to provide a grid-independent load pattern example. Using the COA, the objective of this study is to determine the optimal economic combination for such a system. Taking into account the constraints, the objective function has been implemented, and the results have been presented. The optimization model proposed takes into account the capacity and cost of wind turbines, solar panels, and battery storage systems. The objective of the optimization model is to minimize the total cost of the system while satisfying the demand for energy. The optimization model is formulated as a nonlinear mixed-integer programming problem, which is solved using the COA.

2. METHOD

Due to the unpredictability of energy production from renewable sources, the use of combined systems is a practical and effective solution [22]. With the proper combination of system components, it is possible to achieve an economical, environmentally friendly, and dependable system. The use of hybrid systems disconnected from the grid is an appropriate method for powering remote areas [23]. The hybrid system under study consists of a wind turbine, photovoltaic panels, battery, and converter. The off-grid system under consideration is comprised of wind turbines and solar panels. Additionally, a battery bank has been considered for improved energy storage and reliability. In this system, when the amount of energy produced by renewable sources is insufficient to power the load, the battery supplies the necessary energy. When the production capacity exceeds the demand, however, the excess production energy is stored in the battery (Figure 1).

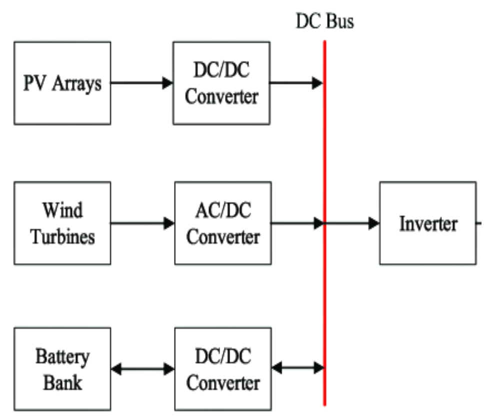

Fig. 1. System configuration.

2.1. Cuckoo Optimization Algorithm

Researchers utilized the COA to determine the optimal economic combination of wind, solar, and battery storage. The behavior of cuckoo birds inspired this metaheuristic optimization algorithm [18]. The objective function was implemented in accordance with the system's constraints, and the outcomes were presented.

The lifestyle of the cuckoo bird inspired the development of this algorithm. The cuckoo's evolutionary algorithm begins with an initial population of cuckoos and cuckoo eggs [24], similar to other evolutionary methods.

The cuckoo population will start to lay eggs in other birds' nests. The host bird detects and destroys any additional eggs. The greater a region's suitability, as measured by the number of eggs that survive and grow, the greater the profit allocated to that region. The cuckoo seeks the optimal location to lay its eggs. The optimal placement is the one that most closely mimics their eggs. Adult cuckoos form communities and groups after attaining maturity. Every population migrates toward the creature with the greatest advantage. Each group constructs a town near the current beneficial position. A number of egg-laying radius areas are estimated and generated based on the amount of eggs that each cuckoo will lay and the distance of the cuckoos from the current best location for settlement.

Randomly, cuckoos lay eggs in nests within their egg-laying radius, or ELR (Fig. 1). This cycle continues until the bird reaches the location where laying eggs is most profitable. This optimal location is where the highest concentration of cuckoos can be found. After multiple iterations, the entire cuckoo population will reach an optimal point where the eggs are most similar to those of the host birds and where there are the most food resources; this location will have the greatest overall benefit and the fewest eggs will be lost [25].

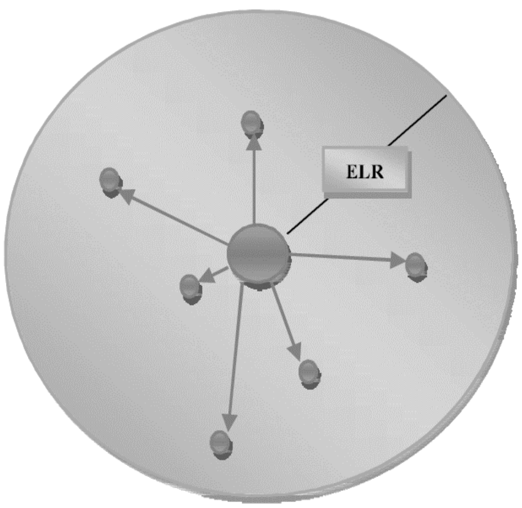

Fig. 2. Cuckoo random laying in ELR domain.

The optimization algorithm's procedure is summarized in the steps below.

1- Determine the primary habitat of cuckoos by selecting a few random points on the function (initial answer).

2-Assigning several eggs to each cuckoo.

3- Calculating the ELR or spawning radius for each egg: The ELR value for each egg is calculated based on the number of eggs and its distance from the target using the following formula: where Var_{hi} and Var_{low} are, respectively, the maximum and minimum values of the decision variables, α is a valid number that determines the maximum ELR. Within their respective ELR ranges, four cuckoos are laying eggs (Equation 1).

$$EIR = \alpha \times \frac{\text{Current cuckoo's eggs}}{\text{Total eggs}} \times (\text{var}_{hi} - \text{var}_{\text{law}}) \quad (1)$$

5- Eliminating eggs with low objective function values.

6- Determining the value of the objective function for each adult cuckoo.

7- Limiting the maximum cuckoo population in the environment.

8- Identifying the optimal cuckoo habitat and classifying cuckoos.

9- Migration of new cuckoos to a better habitat

10- The algorithm terminates if the stop conditions are met; otherwise, the second step is executed.

Table 1 displays the parameters used by the envelope optimization algorithm, which were determined by trial and error.

Table 1. COA parameters.

Parameter	Value
The initial number of cuckoos	50
The minimum number of eggs per cuckoo	3
The maximum number of eggs per cuckoo	5
The maximum number of live cuckoos is	50
Maximum repetition	100
Number of groups or categories	3

3. RESULT AND DISCUSION

In addition to meeting the electric load demand, the number of solar panels, wind turbines, and batteries should be optimized so that the cost of the 25-year system is minimized. The cost of the system includes the cost of purchase and installation, as well as the cost of repairs and maintenance over a period of 25 years, as shown in Equation 2.

$$Minimize\ C_T = C_{Cpt} + C_{Mtn}, \quad (1)$$

Where, C_T is the total cost, C_{Cpt} and C_{Mtn} are the initial annual capital cost and the total annual repair and maintenance cost, respectively. It should be kept in mind that the entire initial cost is incurred at the beginning of the project and the cost of repair and maintenance will be completed within 25 years. In order to convert the initial cost to the annual cost, the Capital Return Factor (CRF) is expressed as Equation 3.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (3)$$

Where, i is the interest rate and n is the system's lifetime. In this design, the battery's lifespan is considered to be 5 years, which is obtained by using Equation 4 the current value of the battery.

$$C_{\text{Batt}} = P_{\text{Batt}} \times \left(1 + \frac{1}{(1+i)^5} + \frac{1}{(1+i)^{10}} + \frac{1}{(1+i)^{15}}\right) \quad (4)$$

Where, C_{Batt} is the current value of the battery and P_{Batt} is the price of the battery. In the same order, the lifetime of the converter is assumed to be 10 years, which is obtained by Equation 5, the current value of the converter.

$$C_{\text{Conv/Inv}} = P_{\text{Conv/Inv}} \times \left(1 + \frac{1}{(1+i)^{10}}\right) \quad (5)$$

Where, $C_{Conv/Inv}$ is the current value of the converter and $P_{Conv/Inv}$ is the price of the converter. Therefore, the total initial annual capital cost is equal to:

$$C_{Cpt} = CRF \cdot [N_{WT} \cdot C_{WT} + N_{PV} \cdot C_{PV} + N_{\text{Batt}} \cdot C_{\text{Batt}} + N_{\text{Con / Inv}} \times C_{\text{Conv / Inv}} \quad (6)$$

C_{WT} and C_{PV} are the cost of a wind turbine and a solar panel, respectively. In addition, N_{Batt}, N_{PV}, N_{WT} and $N_{Con/Inv}$ are, respectively, wind turbine, solar panel, battery and converters. Equation 7 can be used to consider the annual cost of maintenance.

$$C_{Mtn} = N_{WT} \times C_{Mtn}^{WT} + N_{PV} \times C_{Mtn}^{PV} \quad (7)$$

Where, C_{Mtn}^{WT} and $C_{Mtn}^{PV}$are the annual repair and maintenance costs of wind turbine and a solar panel, respectively.

The constraints used in the optimization model of the cuckoo search algorithm are that the max available number of wind turbines (N_{WT}^{max}), solar panels (N_{PV}^{max}) and batteries (N_{Batt}^{max}) that are integers should not exceed the available value (Equation 8).

$$\begin{aligned} N_{WT} &= \text{Integer}, \quad 0 \le N_{WT} \le N_{WT}^{max} \\ N_{PV} &= \text{Integer}, \quad 0 \le N_{PV} \le N_{PV}^{max} \\ N_{\text{Batt}} &= \text{Integer}, \quad 0 \le N_{\text{Batt}} \le N_{\text{Batt}}^{max} \end{aligned} \quad (8)$$

Another condition in this model is the production capacity of renewable sources, which must be more than the requested load during 24 hours (Equation 9).

$$\sum_{t=1}^{24} (N_{WT} \times p_{WT}(t) + N_{PV} \times p_{PV}(t)) \ge \sum_{t=1}^{24} p_{load}(t) \quad (9)$$

In addition, the following restriction must be in place for the battery:

$$E_{\text{Batt}}^{\min} \le E_{\text{Batt}}(t) \le E_{\text{Batt}}^{\max} \quad (10)$$

In this regard, $E_{\text{Batt}}^{\min}$ is the minimum charge level of the battery, and also $E_{\text{Batt}}^{\max}$is the maximum charge level of the battery, which is equal to the nominal capacity of the battery.

Figs. 7-a and 7-b depicts the average hourly values of wind speed and solar radiation in the studied area for the purpose of modeling evaluation. In addition, the hourly average load shown in Fig. 7-c is presented. Table 2 displays the technical and economic characteristics of the system's equipment. The objective function and constraints were implemented using the cuckoo search algorithm, and the results for ten low-cost systems are presented in Table 3.

Table 2. Technical and economical configuration of system.

System overall Parameter	
i	4%
n	25 (year)
Photovoltaic Panel	
p_{PV}	300 (W)
C_{WT}	300 ($)
C_{Mtn}^{PV}	-
Wind Turbine	
p_{WT}	2.2 (kW)
C_{Mtn}^{WT}	7500 ($)
C_{WT}	120 ($)
Battery	
S_{Batt}	2 (kWh)
P_{Batt}	155 ($)
Converter/Inverter	
p_{Conv}	2.7 (kW)
P_{Conv}	2200 ($)
η_{Conv}	96%

Table 3. The results of the optimal economic combination using the COA.

Optimal System ID	N_{PV}	N_{WT}	N_{batt}	NPC ($)
1	121	26	80	31140
2	125	24	71	31826
3	120	30	75	32312
4	118	30	98	32516
5	116	29	90	32936
6	120	27	85	33187
7	125	29	82	33261
8	118	26	85	33502
9	120	30	80	34001
10	124	27	78	34102

Solar radiation is available between 7 and 20 hours, as shown in the diagram, allowing for the production of solar panels during these hours; after sunset, the excess energy can be stored in batteries. Wind energy, on the other hand, can generate power nearly around 24 hour.

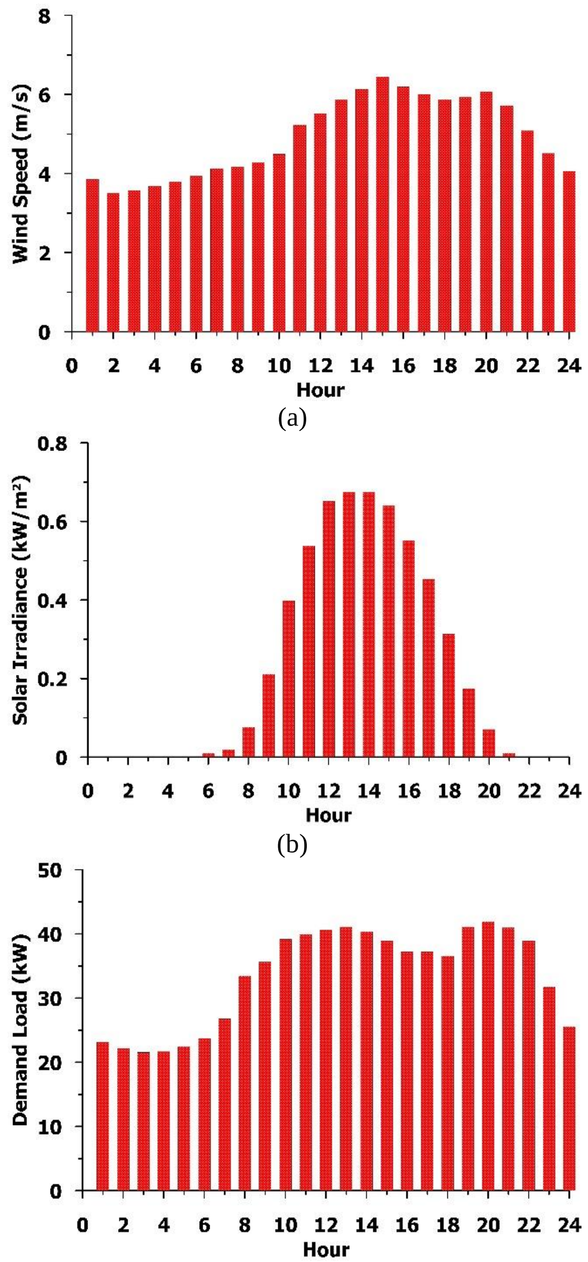

Fig. 3. Hourly average data of a) wind speed, b) solar radiation and c) Demand Load

Table 4 depicts the output power of the wind turbine and solar panels as well as the load demand. Table 4 also depicts the hourly production capacity contribution of wind turbines and solar panels. The state of battery charge is depicted in Table 4. As can be seen, the limit is in place, and the state of battery charge does not exceed the maximum or minimum levels permitted.

Table 4. The results of the optimal economic combination using the COA.

Hour	$Power_{WT}$ (kW)	$Power_{PV}$ (kW)	$Power_{Batt}$ (kWh)
1	17.1	0.0	214.9
2	16.3	0.0	198.9
3	12.7	0.0	182.1
4	11.9	0.0	169.3
5	13.1	0.0	154.2
6	14.5	0.0	145.4
7	14.0	0.5	130.2
8	16.3	1.5	129.4
9	18.9	4.4	112.6
10	23.2	6.9	107.8
11	26.4	10.6	101.4
12	29.7	12.7	107.8
13	33.3	14.2	127.8
14	35.3	13.4	156.6
15	39.2	12.4	183.7
16	40.1	9.1	206.9
17	40.5	6.4	224.5
18	40.6	4.7	235.7
19	38.5	3.8	242.0
20	33.6	2.4	241.2
21	29.2	0.0	241.2
22	25.0	0.0	226.1
23	23.5	0.0	222.1
24	21.7	0.0	215.7

4. CONCLUSION

This study presents a model for the most effective configuration of a combined system that incorporates solar and wind resources in addition to a battery for the storage of energy. The model is provided as a service to the reader. The model is presented in the following paragraphs for your perusal. It is not something that should come as a surprise to anyone that picking out the right wind turbine is of the utmost importance. After completing this stage, the cost-benefit analysis (COA) was carried out in order to identify the configuration of the combined system's components that would result in the lowest total cost while still being able to meet the load demand. The result of these computations led to the conclusion that the system should continue to be operated using the same configuration for the foreseeable future, which is a quarter of a century from now. According to the findings, the optimal hybrid system model appears to have the potential to cut system costs by 10–25% when applied to the production of constant load. This potential cost reduction is indicated by the findings.

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