Paper ID: 320

Optimization of Hybrid Renewable Energy System to Reliably Meet the Electricity Demand of a Small off-grid Island in Bangladesh

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Abstract

Extensive research has been conducted on off-grid hybrid energy systems (HES) for dependable electricity delivery to rural communities. Yet, there is a dearth of research on off-grid hybrid energy sources that can simultaneously supply electric demands. Due to several environmental concerns associated with fossil fuels along with the rapid depletion of fossil fuel reserves, Bangladesh, which relies mostly on a fossil fuel-based electricity generation strategy, must look forward to a renewable energy-based system for a sustainable future. Hence, an optimized renewable energy-based hybrid energy strategy is proposed in this research to concurrently provide electricity to a remote island in Bangladesh. This system consists of solar photovoltaic (PV) panels, wind turbines (WT), backup diesel generators (DG), and battery storage. These elements are optimized using the HOMER Pro software, which is renowned for its capacity to identify dependable and reasonably priced solutions. The result of the research indicates that the PV/ WT/DG/Batt configuration is the most cost-effective option with the lowest cost of energy (COE) (0.356 $/kWh) which is 11.88 % more economical than the next best preference having PV/WT/Batt configuration. The optimized PV/WT/DG/Batt configuration requires a total of 1840 kW PV capacity, 375 kW wind turbine capacity, 100 kW diesel generator capacity, and a battery of 23.876 MkWh. Therefore, this research suggests the most economic HES configuration to be implemented on the selected offshore island in Bangladesh that will reliably meet the electricity demand of the region. This research has created a doorway for future researchers and decision-makers in Bangladesh to implement this strategy on different off-shore islands in Bangladesh to attain a sustainable future.

Keywords: Hybrid energy system, Renewable energy, cost of energy (COE), sustainability, optimization.

1. Introduction

The energy crisis has become a major concern in the 21st century as the global population increased more in this century than in any other century which accelerated the global electricity demand. Many people in rural areas lack access to electricity from central grids. Recent estimates indicate that about 770 million people globally live in off-grid areas. In remote areas, the electricity distribution cost becomes very high which makes it economically unfeasible to connect them to the national power grid [1].

In Bangladesh, 60 million people still lack access to electricity [2]. These areas mainly depend on generating power from non-renewable sources like diesel which is both environmentally harmful for producing greenhouse gas and expensive due to high transportation costs of fuel. Fossil fuels contribute to climate change and environmental disasters due to their extraction and cause many health problems. The quantity of non-renewable sources is limited and will run out within a few decades. Prioritizing renewable energy sources as environmentally suitable substitutes for fossil fuels in energy systems is essential for a sustainable future. By utilizing local renewable sources like solar and wind, these off-grid areas can achieve reliable and cost-effective energy access, improving sustainability and reducing reliance on expensive grid infrastructure.

Hybrid Energy System (HES) configurations are used to achieve the sizing of the components for optimum energy structure, for improving efficiency and reducing energy-related costs. Adding a generator inside an HES provides a sustainable energy backup solution that balances supply and demand and lowers production costs [3], [4]. A HES was designed by Isidro Padrón for a remote area in Spain Canary Islands (Lanzarote and Fuerteventura airport) [5]. The authors designed a photovoltaic (PV), wind turbine (WT), diesel generator (DG), and battery (batt) hybrid system for the coastal area and evaluated it in HOMER. The optimum configuration from the study showed that 69.81% of the total energy comes from renewable energy sources and the rest is from diesel

generators. With this hybrid system, the levelized cost of energy (LCOE) was 0.404$/kWh, and the reduction of CO_2 was 82,651 kg/yr. A case study on Pelee Island analyzed different configurations involving PV/WT/DG /Batt to fulfill electricity demand. With the lowest net present cost (NPC) of $3.67M and LCOE of 0.321$/kWh, the most dependable, economical, and efficient setup includes 152 kW PV, 190 kW converter, 200 kW DG, and 853 kWh battery [6]. Similarly, Ahmed et al. (2024) analyzed for best HES configuration and obtained PV/WT/DG/Batt as the best HES with PV 159 kW, WT 100 kW, DG 60 kW, and 437 kW battery in Saint Martin island of Bangladesh [7]. They showed that a 100% renewable system is not the most economical one by comparing the cost of energy (COE) in four different configurations and the COE of 100% HES (PV/WT/Batt) was 0.1879 $/kWh, which is slightly higher than best system configuration which consists of an extra generator. For meeting the load demand (summer 1130 kWh/day and winter 835.340 kWh/day), the COE of the best economic configuration was 0.1724 $/kWh, which is 77.55%, 8.99%, 134.16%, and 77.55% lower than the COE of the WT/Batt, PV/WT/Batt, PV/Batt, and WT/Batt configurations respectively [7]. High-quality research on HES is still limited and in the remote regions and islands of Bangladesh. Even though a few of study have been done on HES in remote areas in Bangladesh, there is still a significant gap in research concerning the optimal sizing of HES for island communities in Bangladesh. The majority of studies ignore the larger needs of the entire community in favor of concentrating mostly on electricity generation for household consumption. The effects of different HES configurations on the environment, human health, and associated costs have not been reported in the literature. The study's core objectives include emissions assessment, meeting load demand in a cost-effective and environmentally sustainable manner and analyzing the feasibility of various HES configurations on a remote island in Bangladesh. Several key objectives of this study include attracting investors to establish sustainable HES solutions for these remote communities. Moreover, this study shows a high potential of renewable energy-based HES systems to create positive environmental outcomes.

2. Materials and methods

HOMER PRO is an extensively used software for simulation and optimization of hybrid energy systems that integrates various energy sources for effective load supply. The flowchart of the research methodology of this study is depicted in Fig. 1. The process consists of site selection, estimating the energy demand, cost estimation of available resources, and system modeling using HOMER PRO for different system configurations.

Before conducting the modeling, for accurate modeling some key inputs such as renewable energy data (solar and wind), load demand, and temperature were collected, and system components were chosen according to the site's requirements. Time series data sets are entered into HOMER for HES performance simulation, estimation of individual component energy output, and creation of customized energy solutions for off-grid locations. Later, HOMER provides optimized results for the selected configurations.

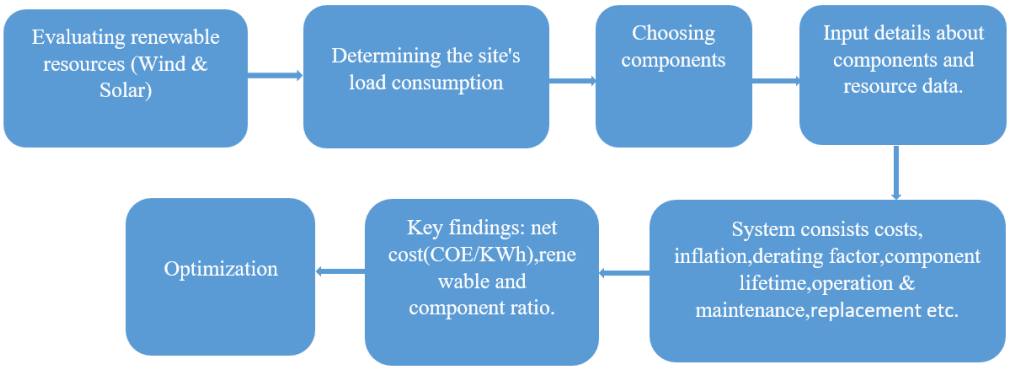
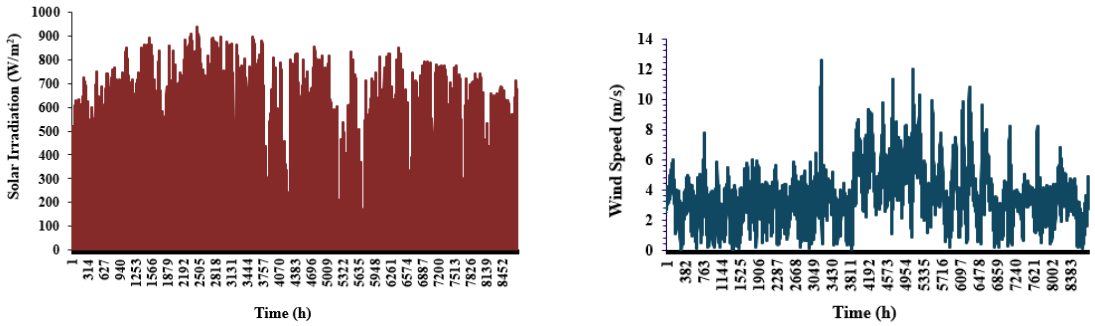


Fig 1: Procedures of the analysis carried out in this study.

2.1 Site description

The study focuses on Dalchar, which is located 213 km away from the capital city of Bangladesh, at Manpura upazila in Bhola district (latitude 21°54′47.37″N and longitude 90°44′29.55″E) and 2 m above sea level [8]. The island consists of an area of 20.97 km² and contains approximately 1,500 houses. The average temperature of Dhalchar is between (15-34) ºC throughout the year. According to the National Aeronautics and Space Administration (NASA) data, the island has a 5.28 m/s average annual wind speed and 4.25 kWh/m²/day average solar irradiation [9]. The hourly solar irradiation and wind speed are shown in Fig. 2, respectively.



(a) (b)

Fig. 2. (a) Time resolved (hourly) solar irradiation, (b) Time-resolved (hourly) wind velocity.

2.2 Load estimation

The Dhalchar island community consists of approximately 1,500 houses, 20 hotels, 3 educational institutions (2 primary schools and 1 secondary school), 1 healthcare facility, and 40 shops. The highest load demand of energy consumption comes from households with 11,340 kWh/ day in summer and 8,730 kWh /day in winter. In summer, the total estimated load demand for the community is 11,710.91 kWh/day. This includes 11,340 kWh/day from households, 326 kWh/day from hotels, 14.26 kWh /day from educational institutions, 7.039 kWh /day from the healthcare facility, and 23.60 kWh/day from shops. In winter, total load demand decreases to 9,011.86 kWh/day. In winter, educational institutions use 3.466 kWh /day, the healthcare facility requires 6.789 kWh/day, and shop demand is 5.60 kWh/day.

2.3 Designing of HES

The main goal of designing HES is to determine the most cost-effective system and energy management to supply load demand in remote areas. An overview of the HES modeling design of this study is shown in Fig. 3, and the component costs and technical characteristics are provided in Table 1 [10].

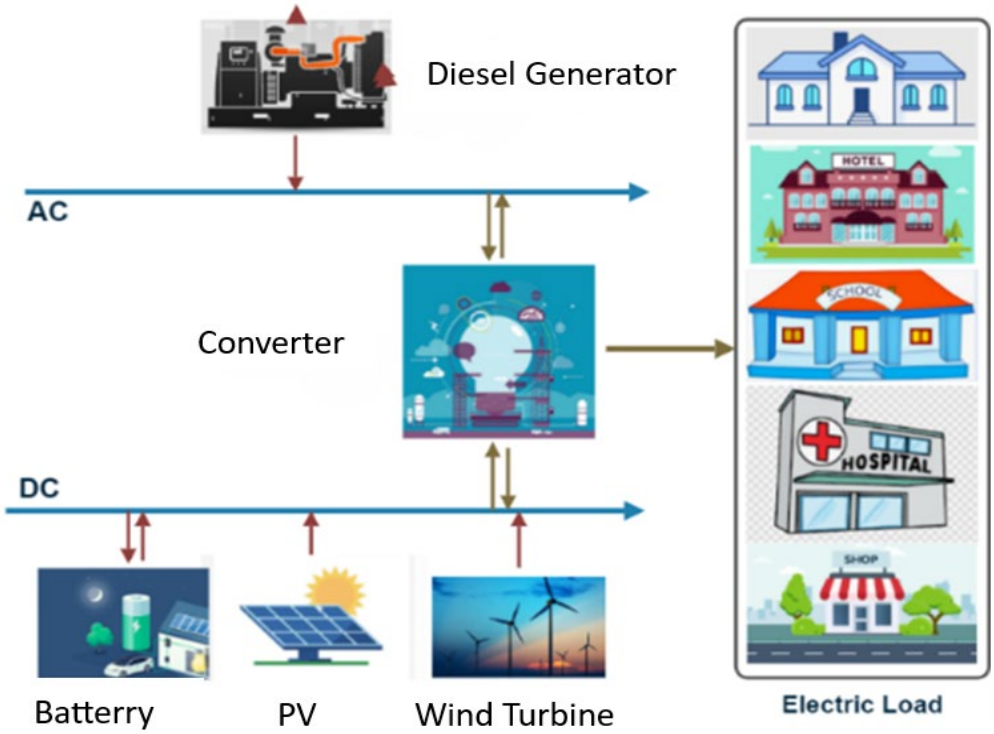


Fig. 3. Schematic layout of the proposed HES.

Table 1. Technical specifications and related costs of the HES

Particulars	Component Specifications				
	PV Module (327 W)	**Wind Turbine (10 kW)**	**Lead-Acid Battery (1 kWh)**	**Diesel Generator (100 kW)**	**Converter 1KW**
Capital	1300$/KW	2300 $/KW	300 $/Unit	220 $/kWh	300 $/KW
O&M Cost ($/year)	20	20	10	262.3	10
Replacement Cost	-	1500$/KW	300$/Unit	220 $/kWh	300 $/KW
Derating factor (%)	80	-	-	-	-
Life (year)	25	20	25	-	15
Hub height (m)	-	20	-	-	
Efficiency (%)	-	-	80	-	95
Fuel price				0.87$/liter	
Reference	[11]	[12]	[12]	[11]	[11]

Cost of energy

The cost of energy was determined in this study using the equation-

$$\text{COE} = \frac{NPC \times CRF(i,n)}{Annual\ Energy\ Served} \quad (1)$$

Where, NPC is the net present cost, and CRF is the capital recovery factor

2.4 Life cycle emission (LCE)

Each component considered in this study contributes to greenhouse gases and other pollutants. Using equation (2) LCE value was calculated [13].

$$LCE = \sum_{m} \sum_{i=1}^{T} \Psi_m E_{m,i,m\in\{PV,WT,DG,Batt\}} \quad (2)$$

Here, E_m denotes the amount of energy stored by the components over T (8760 hr) and Ψ_m represent the lifetime CO_2 emission. Table 2 reports the CO_2 emissions for the various HES components.

Table 2. Equivalent LCE for different hardware components

HES Components	LCE (kg CO_2-eq/kWh)	Reference
Solar PV module	0.045	[14]
Wind turbine	0.022	[14]
Diesel engine	0.880	[15]
Lead acid battery	0.028	[13]

2.5 Job creation

The implementation of HES creates a heavy opportunity for the people by creating sources of work. This job creation depends on the system component of HES configuration. Job creation is calculated for each component by summing the job opportunities from manufacturing, construction and installation, operation and maintenance, and decommissioning, and then multiplying by the regional factor of 2.06 for South Asia [16]**.** Job creation factor for PV 2.7 Jobs /MW and for WT 1.1 Jobs/MW[15]. The computation formula for the job creation number is below:

$$JC = \sum_{n} f_{JC,n} \times P_n, n \in PV, Batt, and\ Backupgenerators \quad (3)$$

Where f_{JC} is the job creation potential of a component and P is the total capacity of that component. The relevant information for calculating the employment factors along with the regional multiplier can be found in [16].

2.6 Impact on human health and ecosystem

The disability of human organs or the violation of physiological function that results in disease and immature death is referred by damage to human health (DHH). Some health problems such as respiratory disease and many types of cancer can be caused by the pollutants emitted due to the implementation of HES. In the same way, the damage or destruction of creatures or species that result in the extinction of such species or loss of several of those species due to these pollutants is called a damaging effect on the ecosystem (DES). In order to calculate DHH and

DES, the amount (kg) of different greenhouse gases (CO_2, CO, NOx, SOx, etc.) emitted by the HES setup was estimated [13] as follows.

$$Damage_d = \sum_{e} \sum_{t}^{8760} CF_{d,e} \times R_{e,t}, d \in DHH, DES, and\ e \in CO_2, NO_x, SO_x, etc. \quad (4)$$

Where, $CF_{d,e}$ stands for the characterization factor, and $R_{e,t}$ denotes the emission of a particular greenhouse gases (GHG) over the year. The cost equivalent to DEE and DHH is considered as 79180 $ and 10.17×106 $ respectively [14], [17].

3. Results and discussion

Energy management

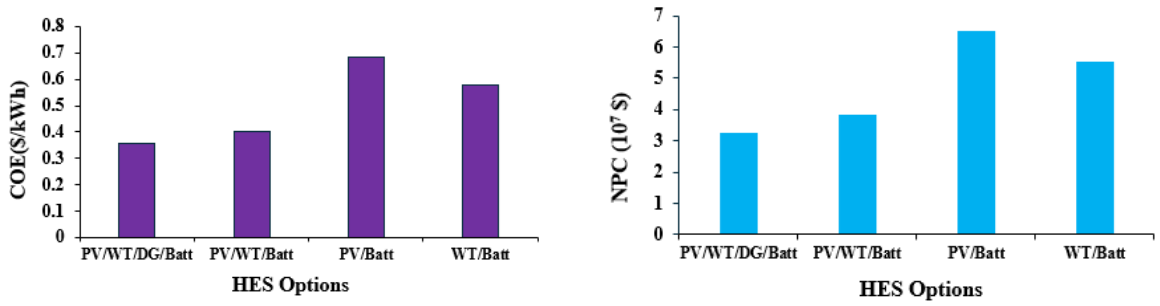
This study deals with the energy management strategies and suitable scale of hybridized micro-grid for an isolated island, Dhalchar in Bangladesh. Results of the optimization procedure are shown in Table 3. This study reveals that minimum PV size is expected for the PV/WT/DG/Batt configuration compared to the others. Besides, battery capacity is also the lowest for the same configuration. Although the WT sizing is not the lowest for this configuration, the total NPC of the PV/WT/DG/Batt configuration is the lowest which makes it the most suitable configuration in terms of economy.

Table 3. Results of the optimal HES for different techniques

Parameters	PV/WT/DG/Batt	PV/WT/Batt	PV/Batt	WT/Batt
LCOE ($/kWh)	0.356	0.404	0.683	0.580
TNPC ($)	3.26×10^7	3.85×10^7	6.51×10^7	5.52×10^7
PV (kW)	1840	2392	8092	–
WT (kW)	375	315	–	1096
Battery Capacity (kWh)	23895	33870	74614	43536
Battery Energy (kWh/yr)	824471	1427677	2391806	1327188
PV energy (kWh/yr)	2.44×10^6	3.18×10^6	10.76×10^6	–
WT energy (kWh/yr)	6.77×10^6	5.69×10^6	–	19.8×10^6

Economic assessment

The economic assessment of different configurations shows that the minimum COE is obtained from PV/WT/DG/Batt configuration (0.356 $/kWh) and the maximum (0.683 $/kWh) for PV/Batt configuration as shown in Fig. 4(a). The COE of the PV/Battery configuration is 15.08%, 27.29%, and 47.87% higher than the WT/Battery, PV/WT/Battery, and PV/WT/DG/Battery configurations, respectively. Hence, it is revealed that although PV/WT/Batt configuration seems attractive as it eliminates the use of non-renewable energy sources, it is not the most economical option. Similarly, as shown in Fig. 4(b), the minimum NPC is obtained from PV/WT/DG/Batt configuration due to minimum sizing of all elements. The NPC of WT/Batt configuration is less than PV/Batt because the cost of PV is higher than WT.



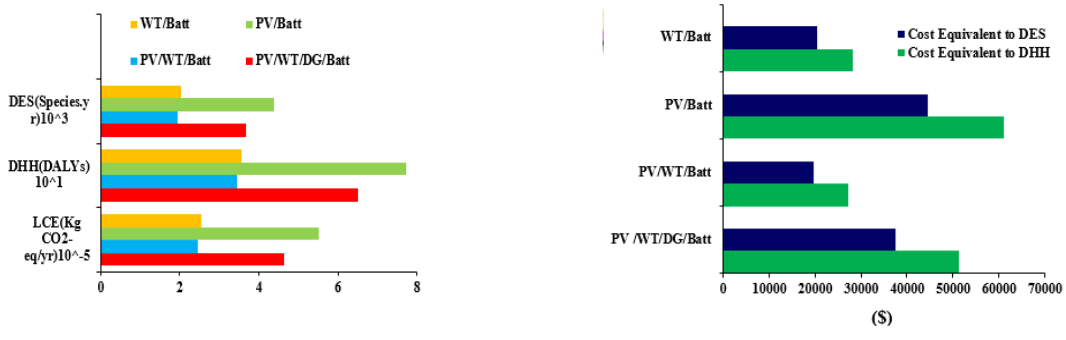
(a) (b)

Fig. 4. (a) COE of different HES configurations, (b) NPC of different HES configurations.

Socio Environmental impact

Environmental analysis

Fig. 5(a) provides a summary of damage to human health (DHH), damaging effects on the ecosystem, and overall lifecycle emission (LCE) for different HES configurations. The DHH, DES, and their equivalent costs are determined based on the amount of CO_2 emissions from different configurations. The lowest (245843.11 kg CO_2 eq/yr) emission comes from PV/WT/Batt configuration. PV/WT/Batt shows a minimum DHH of 0.34 DALY and PV/Batt shows a maximum DHH that is 0.772 DALY. Moreover, the PV/Batt configuration has a maximum DES of 4.37×10^{-3} Species.yr and PV/WT/Batt has a minimum DES which is 1.95×10^{-3} Species.yr. The PV/WT/DG/Batt system has moderate DHH and DES costs due to its balanced use of renewables and a diesel generator. The WT/Batt system has the lowest DHH and DES costs because it produces the least emissions. However, the PV/Batt system has the highest DHH and DES costs because it requires a lot of materials, which has a bigger negative impact on the environment, as shown in Figure 5(b).

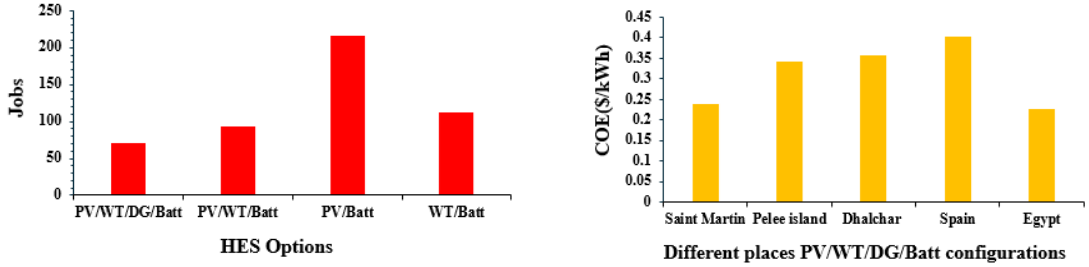


(a) (b)

Fig. 5.(a) Effect of different HES configurations on environment and human health, (b) The monetary valuation of the damage inflicted on ecosystem and human health.

Job creation

Job creation is calculated for each optimized condition. Job creation depends on the capacity of each component and job creation factor [16]. Fig. 6 represents job opportunities that can be created due to the incorporation of the selected HES configurations. From Fig 6(a), it is reflected that PV/WT/DG/Batt offers minimum jobs because of its minimum sizing of the components. The PV/WT/DG/Battery configuration has a lower capacity, resulting in fewer jobs. Because of PV's higher job creation factor than WT, the PV/Batt is expected to offer higher job opportunities than WT/Batt.



(a) (b)

Fig. 6. (a) Job creation potential of different HES configurations, (b) Best system HES configuration comparison.

Comparison among similar investigations:

From different HES configurations, PV/WT/DG/Batt has been the most economical having minimum COE (0.356 $/kWh) which is 13.48%, 91.85%, and 62.92 % lower than PV/WT/Batt, PV/Batt, and WT/Batt configurations, respectively. PV/WT/Batt shows lower DHH and DES compared to PV/WT/DG/Batt configuration as the configuration doesn't involve any diesel generator. A comparison among the COE of different optimal configuration observed in the literature [5], [6], [7], [18] is presented in Fig. 6(b). The optimum best COE in the study differs from other literature because of community load demand, inflation and component price. Additionally, variations in weather conditions, fuel costs, and maintenance expenses in this region can also cause

differences in the COE compared to other studies. In this comparison, the examined COE shows slight differences with the references' best configuration values. The results show that PV/WT/DG/Batt is the best configuration for an HES consisting of the four components.

4. Conclusion

Depending upon the different types of hybrid energy system (HES) configurations, the PV/WT/DG/Batt shows the cost of energy (COE) of $0.356/kWh which is the lowest other HES configurations. Although the PV/WT/Batt arrangement contributes to the minimum emissions, and damaging effect on ecosystem and to human health, PV/WT/Batt is less cost-effective than PV/WT/DG/Batt because of its higher COE. Furthermore, the PV/WT/DG/Batt configuration shows satisfactory performance ensuring a consistent supply of energy, employment creation, and an economic approach. Additionally, this study can provide valuable insights for policymakers, presenting a high opportunity for job creation and the empowerment of local populations which leads to sustainable development. Therefore, considering all factors, the PV/WT/DG/Batt configuration is found to be the optimal choice for hybrid energy systems in the studied region because of its considerable performance with respect to cost, effect on the environment, and proper employment creation.

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