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AN EFFICIENCY STUDY OF PHOTOVOLTAIC/WIND/BATTERY/ELECTROLYZER/H2-TANK/FUEL CELL FOR A REMOTE AREA ELECTRIFICATION

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Keywords: Optimal configuration; Cost of energy (COE); Total net present cost (T_{NPC}); Whale optimization algorithm (WOA); Storage systems.

With the rapid development of the use of renewable energy systems, it is becoming more and more important to combine different sources into hybrid renewable energy systems. Many parameters in hybrid renewable energy systems must be optimized to effectively size hybrid system components to achieve economic, technical, and design goals practically. This paper focuses on the optimal configuration of off-grid hybrid renewable energy systems (HRES). The system consists of a photovoltaic (PV), wind turbine (WT) and battery bank (BB), fuel cell (FC) with hydrogen tank (H2-tank), and electrolyzer (Elect). The optimal size of the proposed HRES component is achieved using a novel meta-heuristic technique called the whale optimization algorithm (WOA). WOA improves the optimal configuration of HRES to produce the best minimum value of the fitness function, which converges to the global optimal solution after several iterations. The proposed WOA is used to solve the multi-objective optimization problem of the cost of energy (COE) in $/kWh and the total net present cost (T_{NPC}) in $. Two recent algorithms, particle swarm optimization (PSO) and gray wolf optimizer (GWO), have also been implemented in this work to demonstrate the effectiveness of the proposed algorithm.

1. INTRODUCTION

Today, due to fossil fuel pollution, limited availability, etc., the use of renewable energy is increasing [1,2]. Because renewable energy is intermittent, a storage system is typically necessary. Hybrid systems consist of a combination of renewable energy sources, consumers, and energy storage. Furthermore, energy storage systems are important in developing new renewable energy systems [3].

Standalone renewable energy systems represent an alternative to grid-connected systems. These systems include solar radiation, wind, and hydro resources, which are essentially inexhaustible. The share of renewable energy generation is expected to increase significantly due to increasing natural gas and oil supply shortages and international awareness and programs to support renewable energy generation [4].

Optimization is one of the most important branches of applied mathematics and has been extensively studied in practice and theory. There are two main optimization methods. One is called deterministic: the search algorithm always solves similarly so that we can determine the search steps in advance. A random algorithm will not always take the same route to the solution and may even present various solutions for initial conditions. Our research will focus on this second strategy, particularly an extremely specialized class of random search method called evolutionary algorithms, which is a crucial tool for solving optimization issues. They are also being utilized in more and more industries. They are simple to use and offer high-quality performance at a reasonable price. Operating a hybrid renewable energy system necessitates maximizing performance while adhering to its technological and physical limitations. Optimization tools, techniques, and applications have become widespread [5] to accomplish these objectives.

Numerous studies have been done on the hybrid PV-wind-battery bank system and the hybrid PV-wind-electrolyzer-hydrogen tank-fuel cell system. Still, very few researchers have employed the hybrid PV-wind with battery bank and electrolyzer-hydrogen tank-fuel cell simultaneously. The design of hybrid renewable energy systems is optimized by [6]. The hybrid power system for electrifying a rural city in Algeria's desert has been designed using particle swarm optimization (PSO) to reduce system costs, loss of load probability (LLP), and CO_2 emissions. [7] developed a hybrid photovoltaic/electrolyzer/fuel cell system when considering reliability and environmental factors for rural electricity.

A factory in Italy that used photovoltaics, an electrolyzer, a hydrogen tank, and a fuel cell was researched [8]. By determining the best series-parallel connection between the two [9] compared the power generated by a PEM electrolyzer stack with a directly linked solar array. Models of photovoltaic modules, fuel cells, electrolyzers, compressors, hydrogen tanks, and batteries were created [10] for three stand-alone photovoltaic power systems that they evaluated utilizing various energy storage technologies.

The integration of photovoltaic, fuel cell, and ultra-capacitor systems for continuous power generation was the focus of [11]. [12] provided a thorough analysis of hydrogen systems fueled by renewable energy sources and their modeling methodologies throughout the previous two decades. For seven villages in the Almara District of Uttarakhand State, India, where various configurations of micro hydropower, biomass, biogas, PV panels, and wind turbines were used, [13] explored four potential scenarios for an integrated renewable energy system. [14] describes a system model and performance evaluation of two decentralized power stations in Sabah, Malaysia, each including a unique arrangement of solar panels, diesel generators, battery banks, and converters.

The primary goal of this study is to optimize the component sizes in a hybrid stand-alone PV/WT/BB/FC system. Timimoun City in Algeria is electrified using a hybrid system. The significance of fuel cell and battery bank systems is also revealed by this study. A novel method

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is suggested for the ideal size of hybrid renewable energy systems. The total net present cost (T_{NPC}) and the cost of energy (COE) of the hybrid power system have both been reduced using the whale optimization algorithm (WOA). The outcomes of our approach are then evaluated against those of the grey wolf optimizer (GWO) and particle swarm optimization (PSO) techniques.

2. DESCRIPTION OF PROPOSED HYBRID SYSTEM COMPONENTS

Photovoltaic panels, a wind turbine, and a storage system comprising a battery bank for electrical energy storage, a fuel cell (FC) with a hydrogen tank (H_2 tank), and an electrolyzer for chemical energy storage comprise the system depicted in Fig. 1. The extra energy from photovoltaic systems and wind turbines is saved in storage systems when it exceeds the demand from the load. A portion of the extra energy is used to charge batteries, while the remaining energy is used to supply an electrolyzer, which produces hydrogen. The H_2 tank is used to hold the hydrogen generated by the electrolyzer. The BB and FC can supply electricity to meet the load when the energy generated by the wind turbines and solar panels is less than required.

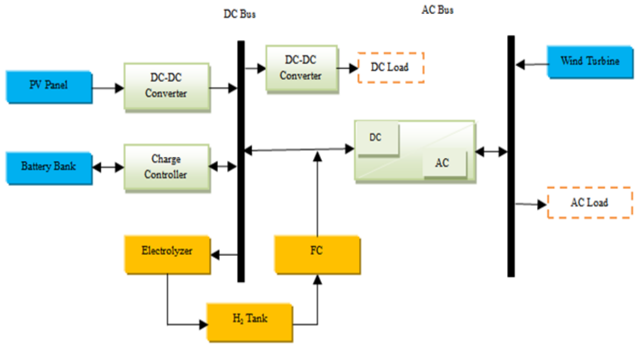


Fig. 1 – The proposed stand-alone PV/WT/BB/FC hybrid system.

3. OBJECTIVE FUNCTION

This article covers the optimal design for a stand-alone hybrid fuel cell, solar, and wind power system with battery storage to satisfy the load requirements of Timimoun City in southern Algeria.

The suggested research is concerned with economic performance, and the best HRES is based on a simulation model developed using MATLAB software. The load profile for Timimoun City is based on real meteorological data. The best system cost analysis is determined using the cost of energy (COE), which is used as the fitness function in this study. COE comprises total net present cost (T_{NPC}), capital recovery factor (CRF), and total electricity generated. The only costs covered in T_{NPC} are total capital cost (T_{CC}), total replacement cost (T_{RC}), and total operation and maintenance cost (T_{OMC}). The parts that must be considered include solar panels, wind turbines, inverters, battery banks, electrolyzers, hydrogen tanks, and fuel cells.

After that, the COE can be calculated as follows [15,16]:

$$\text{COE} = \frac{T_{NPC.CRF(r,n)}}{\sum_{t=1}^{744} E_L}. \tag{1}$$

The load demand is denoted by EL, the interest rate is denoted by r, which in this work equals 0.06, and the component life spans are denoted by n. The following equation is used to get the total net current cost:

$$T_{NPC} = T_{CC} + T_{RC} + T_{OMC}. \tag{2}$$

The capital recovery factor (CRF), defined below [17], is a ratio used to determine the present value of a sequence of equal yearly cash flows

$$\text{CRF} = \frac{d(1+d)^T}{(1+d)^T - 1}. \tag{3}$$

Table 1 summarizes each component's economic and technical parameters considered during system optimization.

Table 1

Components considered in the system optimization

Components	PV panel	Wind Turbine	Bat. bank	Elect.	H_2-tank	FC	Inverter
Capital cost ($/unit)	275.07	33985.02	179.83	1134.72	1000	27062	1491.30
Replacement cost ($/unit)	0	0	10	0	15	0	0
Operation and maintenance cost ($/unit)	35.6	20	1.5	25	30	1	8
Lifetime (year)	25	20	10	15	15	15	20
Efficiency (%)	90	90	85	75	95	50	90
Power (kW)	0.33	1	6.7	0.2	1	6	2.5

4. RESULTS

Each installation component has been defined using MATLAB software's previously mentioned features and data. In this study, we optimize the hybrid PV/wind/battery bank/electrolyzer/H_2-tank/fuel cell system to select Timimoun's remote site's most cost-effective system architecture. We must have all the information from the selected site to construct this electrical system. The load profile, solar radiation, temperature for photovoltaic energy generation, wind speed, initial cost of each component, cost, and project life are examples of typical information. Using these data, we may perform simulations to determine the ideal hybrid renewable energy system configuration for the site under investigation. Analysis of the temperature variance shown in Fig. 2 reveals that the coldest month is January, with an average temperature of about –2°C, and the hottest months are July and August, with an average temperature of about 34 °C. The average monthly temperature is around 22°C.

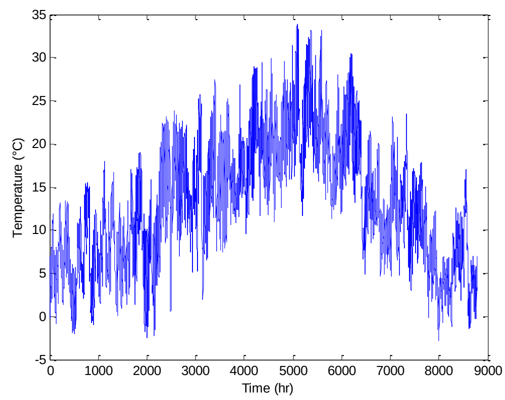


Fig. 2 – The temperature profile.

Figure 3 displays the sun radiation values for the entire year, hour by hour.

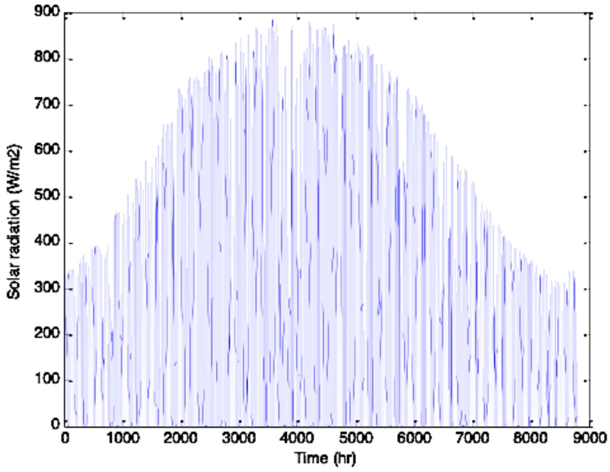


Fig. 3 – The solar radiation profile.

Figure 4 shows how the wind speed profile has changed over the course of the year's four seasons. Since most wind turbines begin operating at wind speeds greater than 3 m/s, the Timimoun site's average monthly wind speed is always greater than 5 m/s. As a result, wind energy development at this location is advantageous. The Timimoun site has a very high potential for wind energy and is suitable for high-power installations.

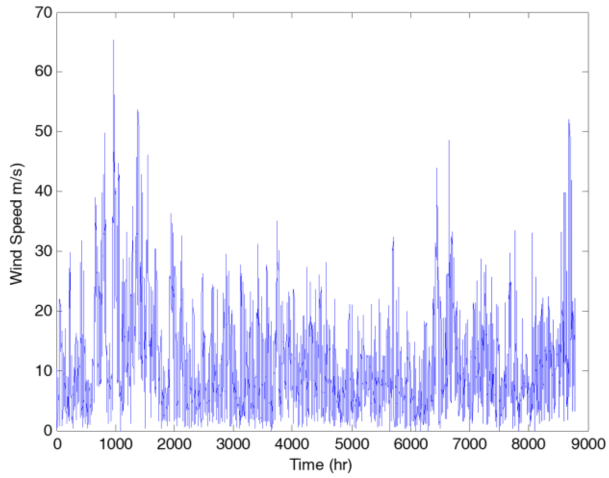


Fig. 4 – The wind speed profile.

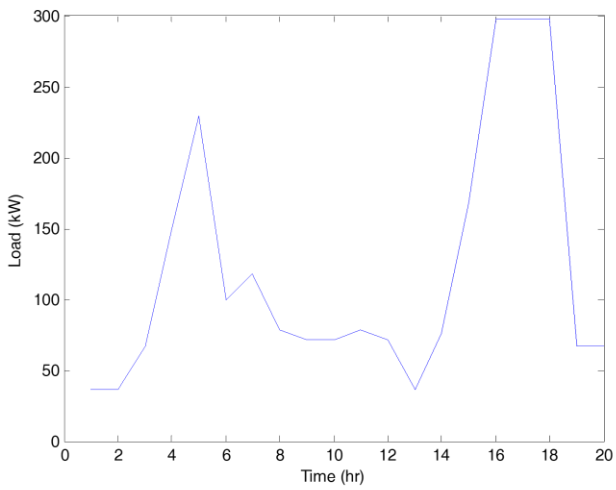
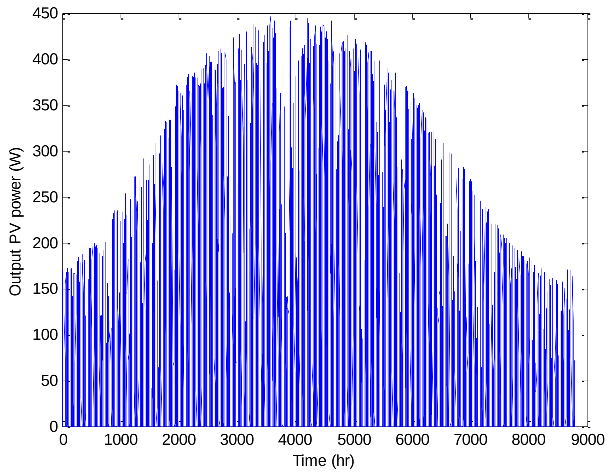


Fig. 5 – The load profile.

Figure 5 shows the energy used on a day in 2020. The energy consumption will be 2.5527 MWh/day, with a peak power of 298.1 kW. The Timimoun site's electricity consumption varies hour by hour, as shown in Fig. 5.

This variation in usage is due to how different night and daytime home appliances operate. Figure 6 presents the various parts of the hybrid system (PV, WT, FC, H2-tank, and Elect), the annual output power of a solar panel, a wind turbine, an electrolyzer, a fuel cell, and the mass of hydrogen stored. For a better understanding, Fig. 6's findings are concentrated on a certain day and 200 hours of system operation.



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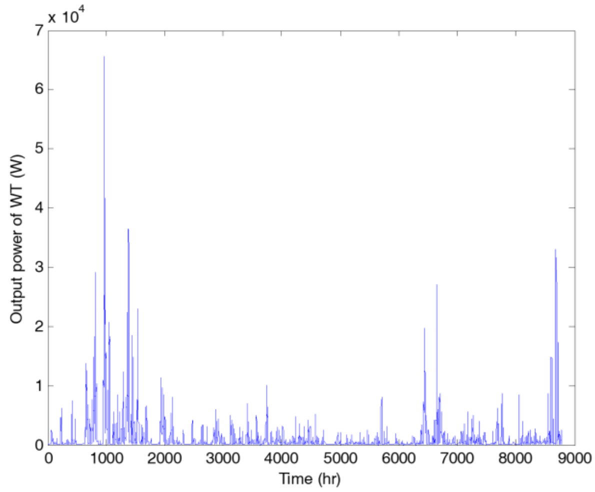

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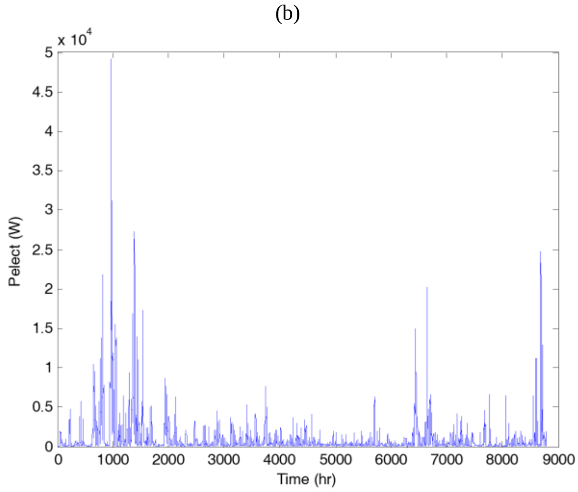

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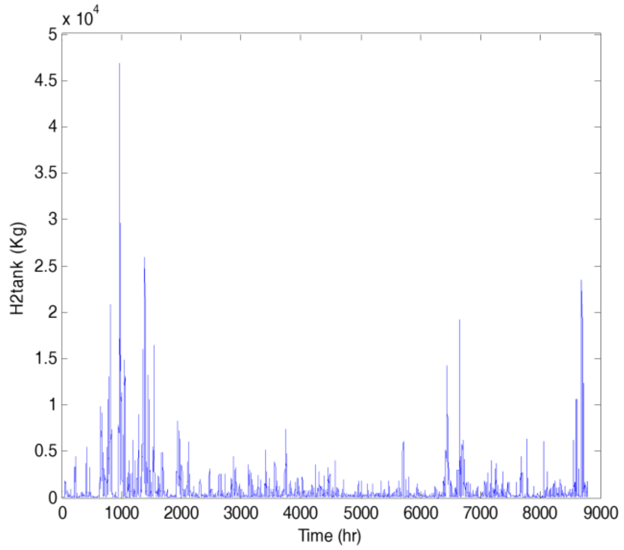

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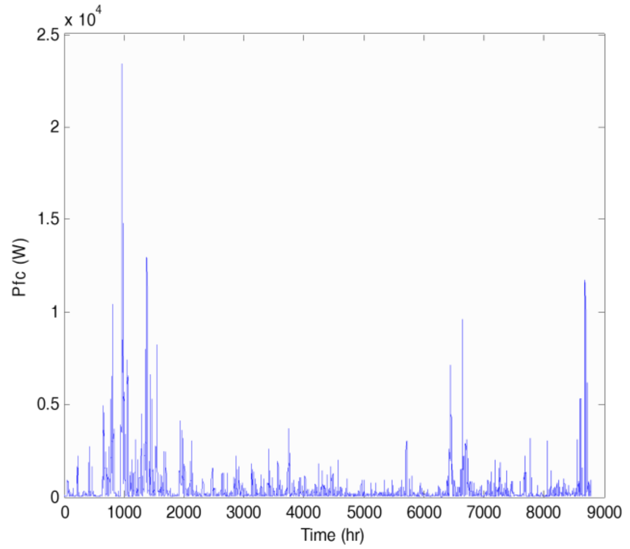

(e)

Fig. 6 – Annual operation of PV/WT/FC hybrid system: a) PV panel output power; b) wind turbine output power; c) electrolyzer output power; d) mass of hydrogen stored; e) fuel cell output power.

Figure 7 shows, using the WOA data, how the PV/Wind/Battery/FC system operated during a certain day (200 hours) compared to the load.

The production shortfall is filled by providing the BB and the FC with the hydrogen stored in the tank when the energy generated by the PV and WT system is missed or insufficient. The electrical power produced by the BB and the FC is reduced as the power produced by the PV and WT systems is gradually raised until the electricity supplied by the renewable sources is adequate to fulfill the load requirements. The excess power is provided to the external national grid when generated by the PV and WT power plants and exceeds the load demand plus the rated electrical power of the water electrolyzer.

Figure 8 depicts the convergence curves of the WOA, GWO, and PSO algorithms for the PV/WT/BB/FC hybrid system. The optimal sizing parameters for the suggested configuration using various optimization techniques are shown in Table 2. They include the number of PV panels (N_{PV}), number of wind turbines (N_{WT}), number of battery banks (N_{BB}), power of electrolyzer (P_{Elect}), mass of hydrogen tank ($M_{H2\text{-}tank}$), power of fuel cell (P_{FC}), power of converter (P_{Conv}), cost of energy (COE), and total net present (T_{NPC}).

These data show that, compared to GWO and PSO algorithms, WOA generates the smallest value of COE and T_{NPC} with quick convergence to the global optimum, which illustrates the excellent reliability of the system under study in this research effort.

The variation of the optimal configuration of the proposed system from one algorithm to another causes the variation of the COE value. From these results, we can also observe that increasing the number of wind turbines will cause the COE to go down and reach the minimum value.

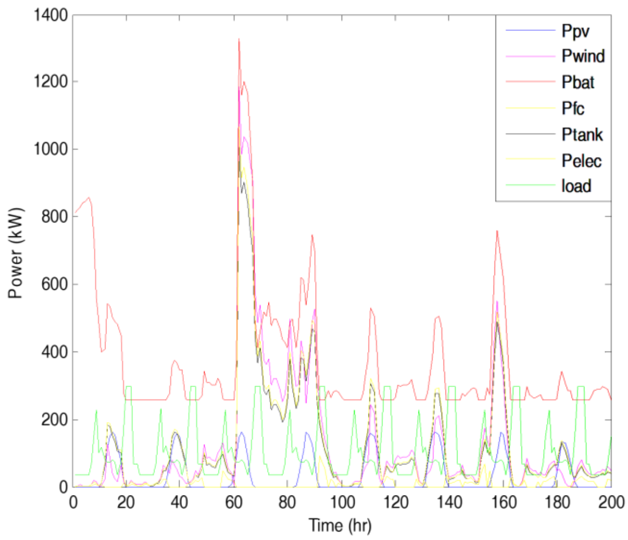

Fig. 7 – Operation of the PV/Wind/Battery/FC system on a certain day (200 hours) compared to the load using the results of WOA.

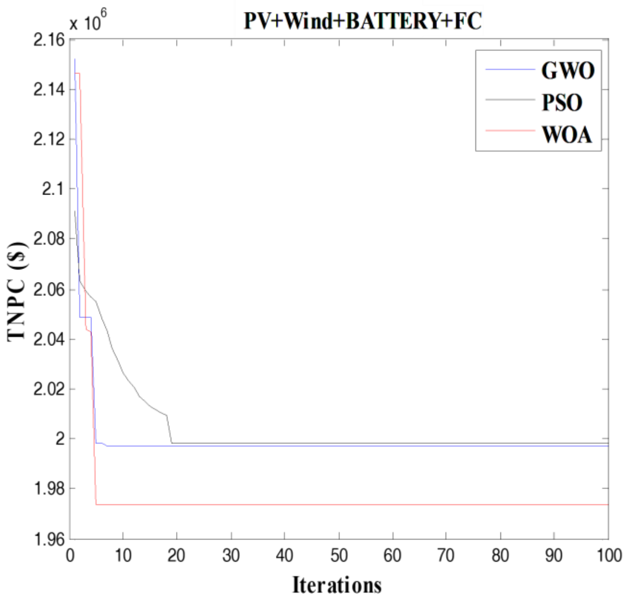

Fig. 8 – Convergence curves for different optimization algorithms: PV/Wind/Battery/FC system.

The expenses of the various system components are shown in Table 3 for the WOA-optimized system.

This table shows that capital cost is the most expensive element in the entire cost system. The capital cost of PV panels, as displayed in Table 3, is the most significant expense.

According to WOA, the system's total capital cost (T_{CC}), total replacement cost (T_{RC}), and total operation and maintenance cost (T_{OMC}) are, in order, 1 971 396.87 dollars, 645.08 dollars, and 1 452.89 dollars. The suggested system can assure the energy supply to the load demand, as shown in Tables 2 and 4. As a result, the suggested setup can save costs by approximately 1 973 494.85 $ with a COE of 0.16 $/kW

Table 2

Optimization results of the system components based on WOA, GWO, and PSO algorithms

	PSO	GWO	WOA
N_{PV}	117	51.78	148.34
N_{WT}	84	50.05	81.19
N_{BB}	95	54.96	97.22
P_{Elect} (kW)	69.47	42.40	54.79
$M_{H2\text{-}tank}$ (kg)	66	31.80	52.05
P_{FC} (kW)	33	30.21	13,03
P_{conv} (kW)	615.93	388.53	683.87
COE ($/kWh)	0.16	0,498	0.16
T_{NPC} ($)	1 998 066.27	1 997 311.37	1 973 494.85

Table 3

Optimal cost results of each component of the proposed hybrid system

Components	OMC ($)	Replacement cost ($)	Capital cost ($)
PV	528.11		191 249.40
WT	310.35		275 926.07
BB	145.84	449.42	17 484.52
Elect	136.99		62 180.38
Tank	156.17	195.65	52 058.10
Fc	13.03		352 631.39
Conv	162.38		1 019 866.98

5. **CONCLUSIONS**

The current study aims to use meta-heuristic techniques to optimize each component's design and technology choices for hybrid renewable energy systems. The suggested hybrid system comprises a converter that enables the transfer of electrically generated energy to the load, a hydrogen tank and battery bank as an energy storage system, a WT, FC, electrolyzer, and a WT/WT/FC/Battery bank. As a challenging optimization problem, the proposed hybrid system has been studied.

The best ideal value for each system component has been determined using the WOA method to solve the optimization problem. Compared to the results given by the GWO and PSO algorithms, the WOA algorithm offers the best solutions. The WOA enhances the hybrid system's ideal configuration, provides the best minimum of the objective function, and, after a few rounds, converges to the overall ideal solution. The PV system was discovered to have the highest system-wide capital cost.

The proposed WOA could resolve future complicated engineering problems.

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