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Enhancing Off-Grid Hybrid Renewable Energy System Designs for Power Generation in Desert Environments: Case Study of Adrar, Algeria

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Abstract

Renewable technologies are essential for sustainable energy development, as they reduce dependence on fossil fuel reserves, improve global energy security, and reduce greenhouse gas emissions. The purpose of this study is to design a stand-alone hybrid solar, wind, and fuel cell power system for a shopping center in Adrar, Algeria with a capacity of 11.26 kWh/day. The proposed optimal design study focuses on optimizing the technical and economic performance based on the lowest total net present cost and energy cost using HOMER Pro software. The results showed that the optimal design consists of 1.91 kW photovoltaic array, five wind turbines, each with a capacity of 3 kW, a 1.77 kW converter, a 10 kW electrolyzer, a 10 kg hydrogen tank, and 10 kW fuel cells. The results revealed that the levelized cost of energy (LCOE) and net present cost (NPC) of this design are 0.8$ and 45589$, respectively. Additionally, as indicated by the national power supplier Sonelgaz, the overall cost of our suggested hybrid system offers a cheap price, particularly in locations more than one km from the electrical grid.

Keywords: *Renewable technologies; shopping center; technical and economic performance; HOMER Pro software; hybrid System; Hydrogen; Adrar region.*

1. Introduction

Despite significant improvements in energy generation, the majority of the world's population continues to lack access to energy, and for those who do, inexpensive and reliable electricity remains a difficulty. Decentralized energy solutions, or off-grid solutions, have emerged as a viable alternative to the traditional manner of distributing electricity to these remote areas. Traditional energy sources account for more than 75% of energy generation worldwide. Grid expansion requires a large capital commitment, which currently appears unachievable, especially for developing economies. The large transmission and distribution losses associated with the practice of extension also make the project unviable for many developing countries. Renewable energy technology has emerged as a result of this obstacle. By 2030, more than 70% of the world's population is expected to have access to electricity through off-grid technologies using renewable energy technologies. The beauty of renewable technologies over conventional systems has to do with environmental safety and providing affordable, reliable, sustainable and modern energy for all. As a result, there is a greater desire to integrate renewable technology on a large scale into existing energy systems. Due to their growing technology, wind and solar energy currently dominate the renewable energy sector [1–11].The use of a single renewable technology, such as photovoltaic or wind power, may result in unreliable power generation due to its intermittency. In such situations, it is wind and solar systems [12–15]. The potential advantages of this hybrid solution can be multiplied if it is used to generate pure fuels, such as renewable hydrogen (H2). Derived from solar electrolysis, hydrogen can be used in fuel cells to generate electricity. In terms of size, energy consumption, costs, CO2 emissions reduction and reliability, this H2-HRES combination offers the potential for system optimization investigation. Researchers worldwide have recently shown increasing interest in H2-HRES systems. The goal is to integrate hydrogen (H2) into hybrid renewable energy systems (HRES) in building settings [16–20].

The current study proposes a design for optimally system setup based on Homer Pro software, powered by wind, sun, and hydrogen storage, with the assistance of an electrolyzer and a fuel cell erected in Adrar (southwest Algeria), as illustrated in Figure 1. The key innovation of this study is the combination of wind and solar energy with hydrogen energy, which improves energy output at the lowest possible cost. The system is suggested for a shopping mall in Adrar, Algeria, with an average daily energy use of 11.26 kWh. The aim is to provide uninterrupted energy without carbon emissions. The paper seeks to attain zero emissions by integrating hydrogen production through electrolysis, wind energy, and solar energy technologies, while also considering hydrogen for energy storage and mobility

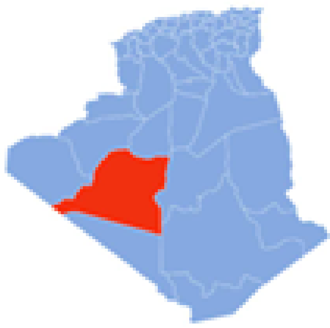

Figure.1: Map of Algeria showing Adrar.

2. Hybrid energy system modeling based on hydrogen

The system's primary goal is to provide electricity to a shopping center while also producing hydrogen to help stabilize the intermittent nature of renewable energy sources. Figure 2 depicts simulations of solar, wind, and hydrogen storage power plants produced with HOMER Pro software

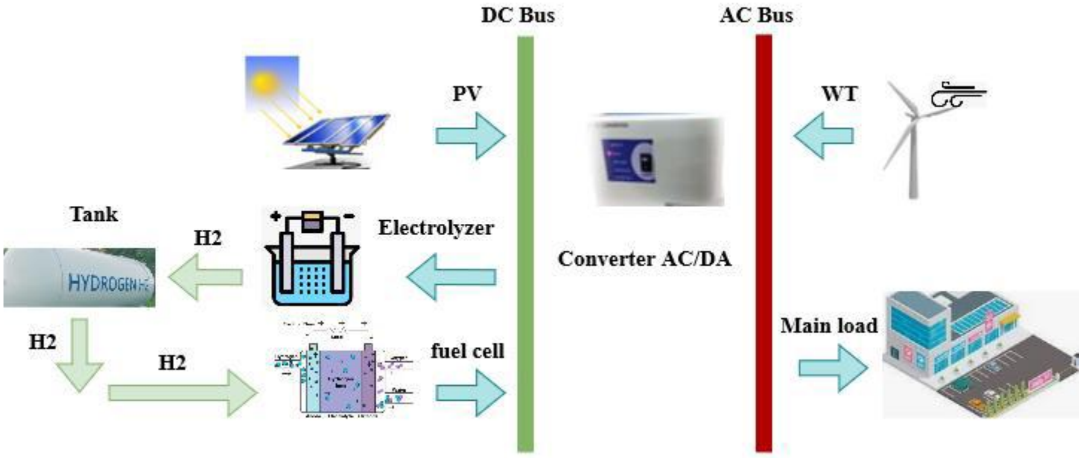

Figure 2: Schematic representation of the investigated hybrid renewable energy system.

a) Wind Turbine

Wind turbines (WT) generate electricity from the accessible and free kinetic energy of the air. Equations (1-4) [21] may be used to approximate WT output power.

Which are used to provide energy to the loads during nighttime hours

$$P_T = P_r \qquad U_r \leq U \leq U_C \tag{1}$$

$$P_T = 0 \qquad U_C \leq U \leq U_{CI} \tag{2}$$

$$P_T = P_r \left[\frac{U(t^3) - U_{CI}{}^3}{U_r{}^3 - U_{CI}{}^3}\right] \quad U_{CI} \leq U \leq U_r \tag{3}$$

$$V_T = U_r \left(\frac{H_T}{H_r}\right) \tag{4}$$

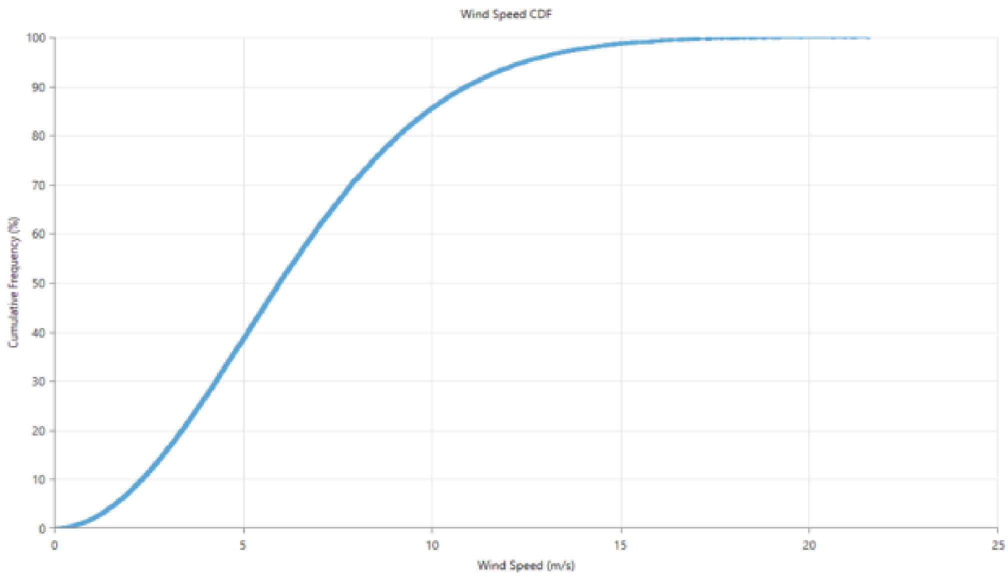

Figure 3: Wind power curve

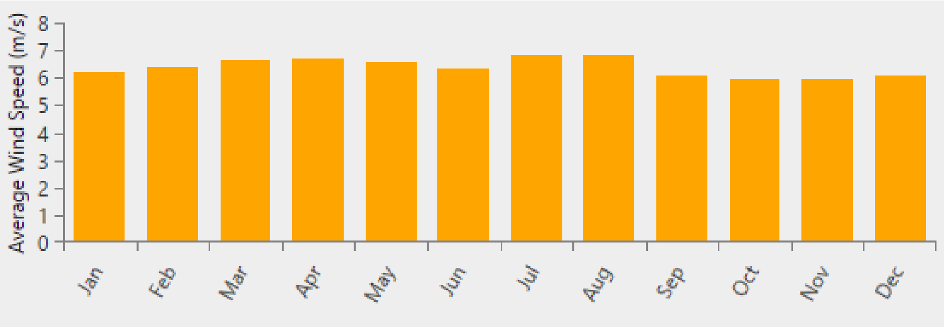

Figure 4: Monthly wind speed.

b) Solar PV

Solar Photovoltaic (PV) is the technology that converts sunlight energy into electricity [22]. Solar panels convert sunlight into direct current, providing free energy without surplus electricity consumption, which is then given to the electrolyzer for hydrogen production. [23].

The equation (5) provides the electrical output of solar arrays [24].

$$P_{PV} = \delta_{PV} \times F_{PV} \left[\frac{G_{PVM}}{G_{STC}}\right] \times [1 + Y_T \times (T_{PVM} - T_{STC})] \quad (5)$$

Figure 5 illustrates the monthly solar radiation, revealing an annual average of 5.87 kWh/m²/day.

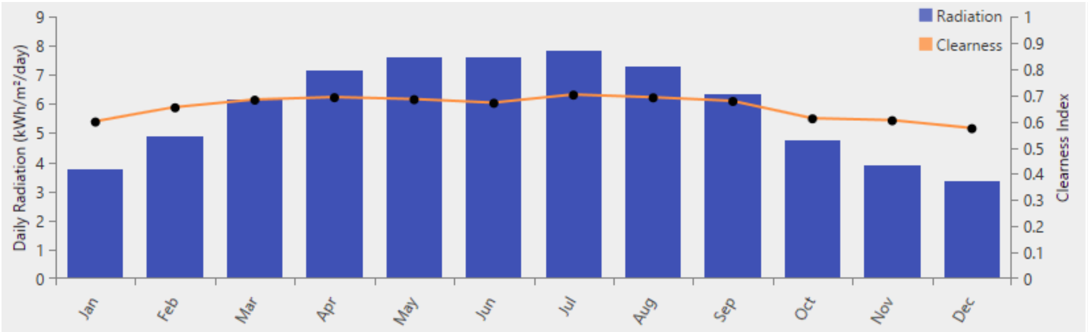

Figure 5: Monthly solar radiation.

c) Converter

The converter is a device that transforms electrical energy from alternating current to direct current.

$$\mu_{converter} = \frac{P_{out-put}(t)}{P_{in-put}(t)} \quad (6)$$

3. Economic analysis

The evaluation of optimization outcomes in HOMER Pro is performed according to many economic criteria.

a) Net Present Cost

NPC is defined as the present cost of the total cost of the system during the project's lifetime, minus the present value of the total revenue accrued during the project's lifetime [25].

$$NPC = \frac{T_{at}}{CRF(i,N)} \quad (7)$$

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (8)$$

b) Levelized cost of energy (LCOE)

The Levelized Cost of power (LCOE) is the quotient of the total costs incurred over the project's lifespan and the total power produced during that same period. (E_i) [26]. The LCOE is calculated as

$$LCOE = \frac{\sum_{i=0}^{T}\left[\frac{C_i + D_i + O\&M_i + K_i}{(1+I)^i}\right]}{\sum_{i=0}^{T}\left[\frac{E_i}{(1+D)^i}\right]} \tag{9}$$

The technical and financial aspects of renewable energy systems (HRES) are identified as shown in Table 1.

Table 1: Input data on option costs.

Option	Capital Cost	Replacement	O&M	Lifetime
Fuel Cell	1000 $	900 $	0.01 $/h/kW	50000 h
PV	900 $	900 $	10 $/yr	25 yr
Electrolyze	1000 $	900 $	10 $/yr	15 yr
Wind Turbine	1000 $	1000 $	10 $/yr	17 yr
Converter	200 $	200 $	10 $/yr	15 yr
Tank	500 $	500 $	10 $/yr	25 yr
Annual interest rate (i)	8%			
Inflation rate (f)	2%			
Project lifetime	25yr			

4. Results and discussion

The table below provides a concise summary of the optimization outcomes obtained from the simulation process with the Homer Pro software

Table 2: Optimized system elements sizing.

PV (kW)	1.91
Wind Turbine (kW)	Five Wind Turbines of 3 KW
Fuel Cell (kW)	10
Converter (kW)	1.77
Electrolyze (kW)	10
Hydrogen Tank (kg)	10
NPC ($)	45589.2
LCOE($)	0.8
Operating cost ($)	1045.79

Following the photovoltaic system's Homer Pro simulation 1.92 kW was the system's maximum power output. Over the course of a year, the photovoltaic (PV) system ran for 4381 hours. The system produced 0.402 kW of electricity on average, with a capacity factor of 21.1%. A annual production of 3521kWh was the result. The power output of the photovoltaic (PV) system is shown in Figure. 6.

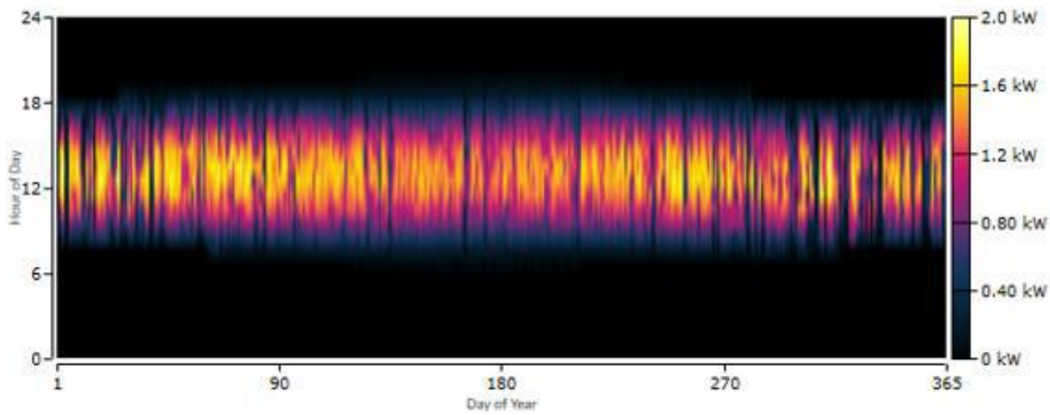

Figure 6: Power generated by the photovoltaic.

According to the simulation's findings, the electrolyze had a 10 kilowatt-hour capacity. Every year, it has been used for 3841 hours. With an average power supply of 0.666 kilowatt and a maximum power input of 3.69 kilowatt, the total energy consumption was 5833 kWh per year. It was found that the rate of hydrogen creation was 0.0794 kg/h. 126 kg in total every year. It has been shown that the average rate of hydrogen generation is 0.0143 kg/h. Throughout the course of the year, Figure. 7 displays the electrolyze input power.

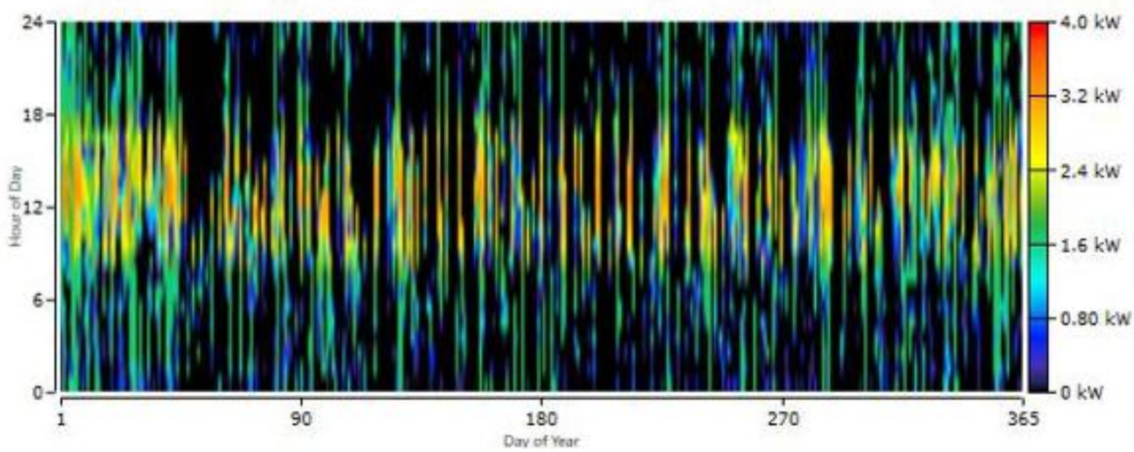

Figure 7: Power generated by the electrolyze.

The generator of the fuel cell could produce 10 kW. Every year, it experienced 673 restarts and ran for 2892 hours. The fuel cell has produced 558 kWh of electricity annually. With a little greater potential output of 1.02 kW, the mean power output is determined to be 0.193 kW. The daily hourly production of fuel cells in kilowatts is shown in Figure. 8. The fuel usage was 0.210 kg/kWh, resulting in a total fuel consumption of 117 kg. 3905 kWh of fuel were used over the year, and 14.3% of it was used on average for electric power use. When solar energy is insufficient, the fuel cell's main function is to generate electricity. In accordance to the modelling findings, the hydrogen fuel cell's power factor was 0.637%. With these specific operating conditions, the fuel cell has an anticipated 17.3-year service life. Since the simulation is expected to run for around 25 years, Therefore, It can be said that there is only one alternative to fuel cells.

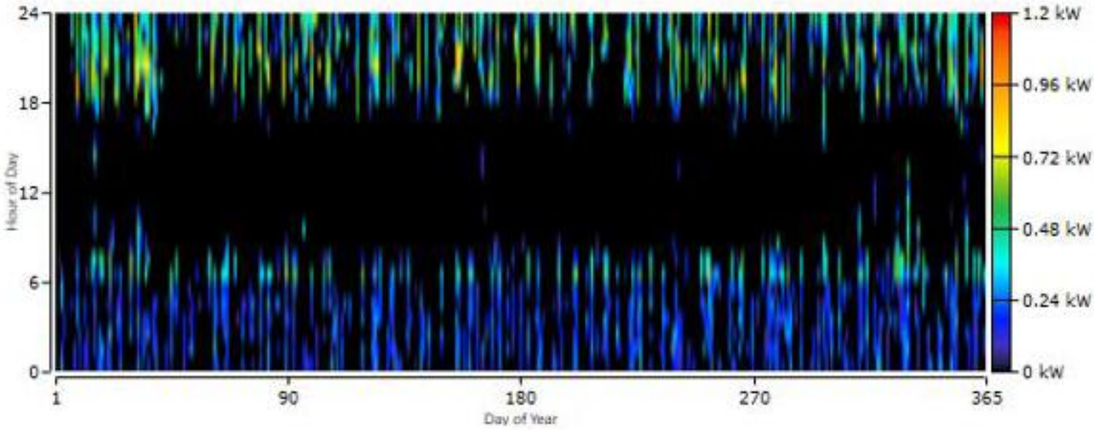

Figure 8: Power generated by the fuel cell.

A peak output of 15 kilowatt was achieved from the simulation of the wind turbine system. With a capacity factor of 29.8% and an average output of 4.46 kilowatt, the system operated for 7528 hours. hours a year. As a result, 39105 kilowatt-hour were produced annually in total. The wind power production is shown in Figure .9.

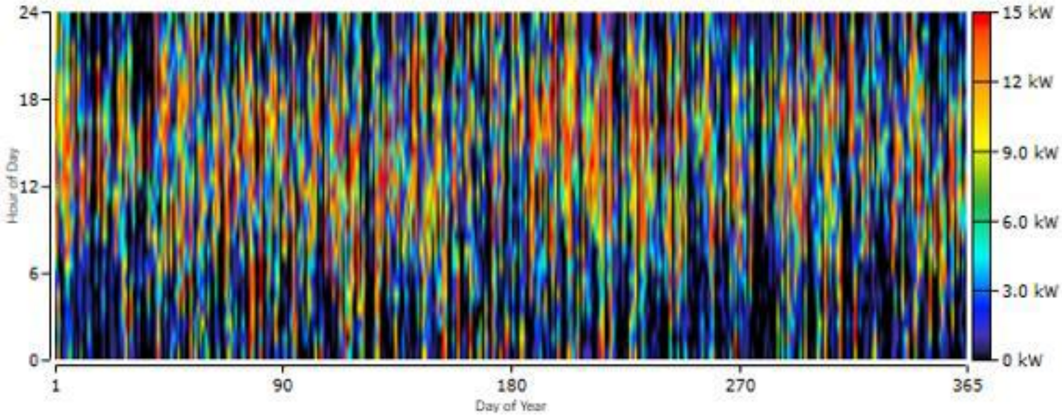

Figure 9: Power generated by the Wind turbine.

The hydrogen tank weighs 10 kg and produces 333 kilowatt-hours in total. Figure 10 depicts the hourly weight of the hydrogen tank in kilogrammes. The hydrogen tank autonomy was calculated to be 711 hours, which is the ratio of the peak energy produced by the hydrogen tank to the electrical demand load. The hydrogen tank levels for the entire year may be viewed in Figure 11. The candle graphic depiction depicts the levels of hydrogen. The overall electricity production for the entire year amounted to 43184 kilowatt-hour. The hydrogen fuel cell accounts for 1.29% of the total electricity generation, which is equivalent to 558 kilowatt-hour per year. The wind turbine system is the dominant power producer, accounting for 90.6% of the total system output, equivalent to 39105 kilowatt-hour annually and the photovoltaic system represents 8.15%, which is equivalent to 3521 kWh/year. The electric load accounted for 41.3% of the aggregate electricity production. The yearly electrical load usage was calculated to be 4109 kilowatt-hours. The combined effect of capacity shortfall and unmet electric load accounts for 0% of the overall electricity demand. The system was found to generate a surplus of 32982MWh/year of power.

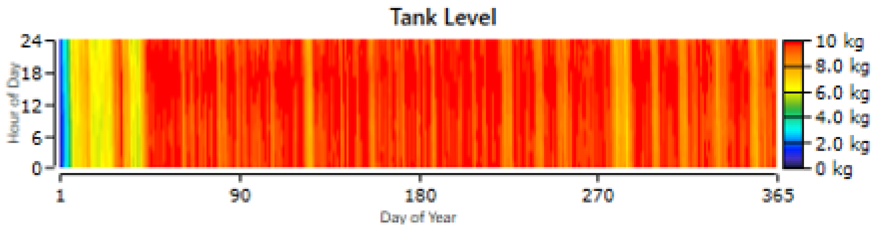

Figure 10: The level of hydrogen in the tank.

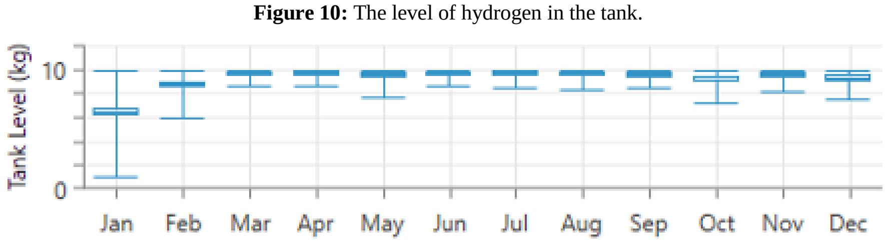

Figure 11: Hydrogen tank level measured on a monthly basis.

Table 3 summarizes the relevant costs for each component of the system.

Table 3: Costs for each elements of the system.

Elements	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
PV	1715.00	0.00	246.34	0.00	1961.34
Electrolyze	10000.00	3818.46	1292.75	718.67	14392.54
Fuel Cell	10000.00	3350.16	3738.64	1194.44	15894.36
Converter	354.70	150.49	229.27	28.32	706.13
Wind Turbine	5000.00	1594.04	646.38	898.34	6342.07
Hydrogen Tank	5000.00	0.00	1292.75	0.00	6292.75
System	32069.69	8913.15	7446.12	2839.77	45589.19

Figure. 12 displays the Cost summary of all the components. considered in the analysis generated by the HOMER software.

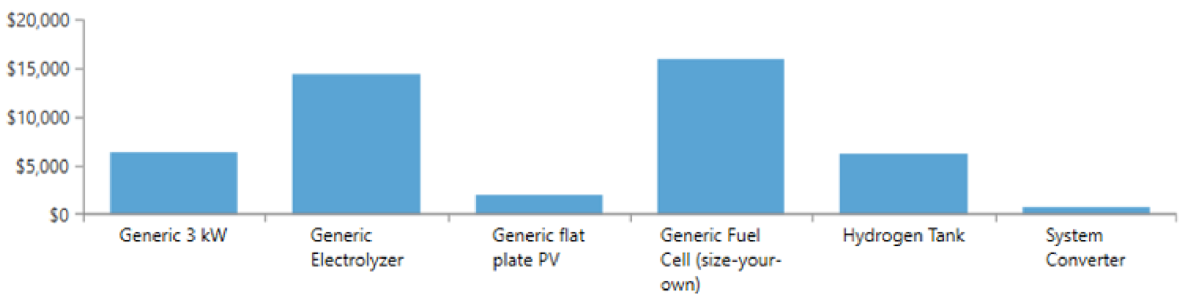

Figure 12: Cost summary.

Table 3 shows that the cost of our system was 45589.19 $, or roughly 6,043,230.08 Algerian dinars., which is less than the cost of establishing a line in an isolated or somewhat remote area starting from 1km by the national electricity provider (Sonelgaz), which costs approximately 6,431,483.53 Algerian dinars in addition to the electricity bill (as reported by the national electricity provider Sonelgaz). Furthermore to the usefulness of our hybrid system, from the point of view of safety and operating autonomy. There is also a saving on the price of energy, particularly in areas more than a kilometer away from the electricity network.

Table 4: Annual emissions of the hybrid system.

Pollutant	**Emissions (kg/yr)**
Carbon dioxide	-0.0368
Carbon monoxide	0.0234
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	0
Nitrogen oxides	0.00234

5. Conclusion

Based on the modelling findings acquired from the HOMER Pro software to supply an shopping mall in the city of Adrar in southeastern Algeria with a capacity of 11.26 kWh/day of electricity, the levelized cost of energy for the optimal design was 0.8$ and the net present cost was 45589$. The modeling results indicate that the system consists of a 1.91 kW photovoltaic array, five wind turbines, each with a capacity of 3 kW, a 10 KW electrolyze, 10 kW fuel cells, a 1.77 kW converter and a 10 kg hydrogen tank. The cost of our system was 45,589.19$, or approximately 6,043,230.08 Algerian dinars, which is less than the cost of setting up a line in an isolated or somewhat remote area starting from 1 km by the national electricity provider Sonelgaz.In the future, we want to develop a hybrid system that uses more sustainable energy and capacity sources to connect such systems to industrial consumers over long distances. Therefore, I suggest that it would be useful to conduct further research on this topic.

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