A Techno-Economic Feasibility Study of Electricity and Hydrogen Production in Hybrid Solar-Wind Energy Park. The Case Study of Tunisian Sahel

Slah Farhani
Computer laboratory for Electrical Systems, INSAT, LR11ES26, University of Carthage, Tunisia | University Kairouan, ISSAT, 3100, Kairouan, Tunisia
slahfarhani20@gmail.com (corresponding author)

El Manaa Barhoumi
Department of Electrical and Computer Engineering, College of Engineering, Dhofar University, Oman
ebarhomi@du.edu.om

Haytham Grissa
Laboratory of Computer and Industrial Systems (LISI), INSAT, University of Carthage, Tunis, Tunisia
grissahaythem@gmail.com

Mohamed Ouda
Telecommunication and Network Engineering Department, College of Engineering & Technology, University of Doha for Science and Technology, Qatar
mohamed.ouda@udst.edu.qa

Faouzi Bacha
Department of Electrical Engineering, ENSIT, University of Tunis, Tunisia
faouzi.bacha@esstt.rnu.tn

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ABSTRACT

This paper provides a comprehensive analysis of the potential for integrating renewable energy sources to meet the growing electricity and hydrogen demand in the Tunisian Sahel region, focusing particularly on solar and wind energies. The feasibility of installing a hybrid solar-wind energy system capable of producing both electricity and hydrogen is evaluated. With the help of the available solar and wind resources combined, the system not only generates electric power, but also produces hydrogen gas through electrolyzation, hence offering a multipurpose solution in terms of storage and supply. This flexibility is crucial due to the variability of renewable resources, which change daily and seasonally. The paper outlines the optimization process for designing the hybrid system deploying HOMER Pro software, according to local climatic conditions and demand profiles. The economic analysis reveals that the system can produce an average of 101.8 kg of hydrogen daily with a total photovoltaic capacity of 3,000 kWp, resulting in a project net cost estimation of approximately 5,494,912 euros. This analysis provides valuable insights for stakeholders considering similar projects, including the costs associated with photovoltaic systems, electrolyzers, and hydrogen storage solutions.

Keywords-hydrogen; renewable energy; hybrid energy production; economic feasibility

I. INTRODUCTION

Hydrogen is emerging as a globally significant energy carrier, exhibiting excellent dynamism as an energy paradigm [1]. This versatility holds great promise for fulfilling the increasing energy demands and presenting a wide range of application possibilities [2]. Projections indicate that by 2020, hydrogen's contribution to the global energy landscape could reach 8%, with production costs ranging around $2.5 per kg [3]. By 2050, a surge in hydrogen demand is anticipated, potentially reducing production costs to less than $1.8 per kg [4], posing a significant challenge in the management of modern energy, requiring producers to prioritize environmentally sustainable methods [3]. Renewable energy installations, including wind, solar, biomass, geothermal, and tidal energies, are experiencing a rapid growth worldwide, expanding the installation capacities to unprecedented levels [5].

This paper extensively examines the production of green hydrogen utilizing solar and wind energies, and its impact on the techno-economic landscape of Tunisia. It conducts a thorough techno-economic assessment of a dedicated hybrid solar-wind system situated in the hinterland, serving both as a hydrogen refueling station and electricity generator [6]. The assessment encompasses the costs associated with the hydrogen station equipment, electricity generation, and the solar and wind potentials in Tunisia's Sahel region. In this context, the paper aims to provide a comprehensive analysis of the project costs, the Levelized Cost of Hydrogen (LCoH), and the electricity production costs.

II. RENEWABLE ENERGY SYSTEM PRESENTATION

Essential parts of the proposed poly-generation system's design are the Photovoltaic (PV) panels, Fuel Cells (FCs), and electrolyzers with a relevant infrastructure to promote storage tanks for electric and hydrogen-based consumption [7]. The electrical demand system caters to applications, such as lighting and small motor pumps, while the produced hydrogen is intended for powering FC Vehicles (FCVs) at charging stations, particularly serving the hospitality sectors of the Sahel region and specifically those of the Kantoui area.

A. *Location Renewable Energy Potential*

Concerning its geographical context, the system is located in Sousse. Sousse is geographically located between 35° 49' 17.1480" N and 10° 38' 3.9192" E. This area is characterized by a satisfactory potential in exploiting energy power, including the abundant solar resources, adequate wind strength, and high tidal energy.

The current study utilized the HOMER software to derive precise estimations for the net profit and the LCoH. This software relies on detailed renewable energy metrics as inputs, including solar irradiance, wind velocity, and ambient temperature. Accurate data concerning these parameters were meticulously collected and inputted into HOMER [8]. Solar radiation data, specifically, were obtained from NASA's Atmospheric Data Center, pertaining to the Sahel region of Tunisia bordering the sea. The monthly average solar power was determined and standardized using data acquired this month from the Global Horizontal Irradiation for 2023, with the former peaking at 7.5 kWh/m^2/day, as illustrated in Figure 1. The analysis considered a 25-year lifespan for the PV system, an 80% de-rating factor, and an assumed ground reflectance of 20%.

Situated near the Tunisian Sahel coastline, this area is spotted with excellent wind energy potential [9]. Its analysis demonstrates that the mean wind speed per month has never gone below 5 m/s, especially during the months of February and April, with an overall average wind speed of about 8 m/s as displayed in Figure 2. Furthermore, temperature presents fluctuations ranging from 14 °C to 29 °C throughout the year as depicted in Figure 3, suggesting favorable conditions for PV installation in the region [10]. These factors collectively contribute to an integrated environmental and climatic profile, highlighting the region's capability not only to harness solar energy, but also wind energy, thereby confirming its potential suitability for hosting the proposed hybrid solar-wind energy system [11].

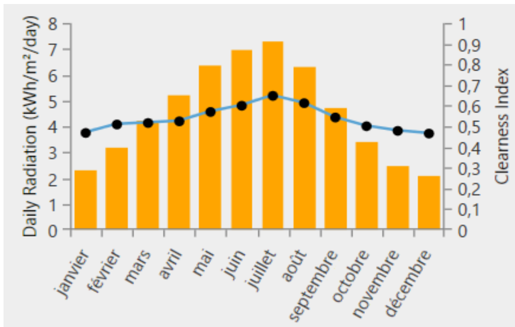

Fig. 1. Average daily solar radiation at the site.

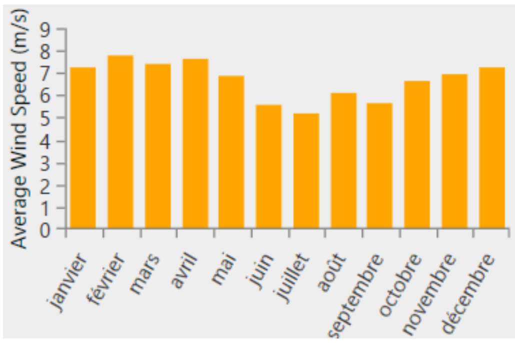

Fig. 2. Monthly average wind speed at the site.

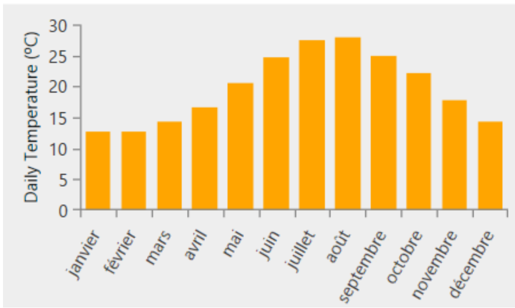

Fig. 3. Average daily temperature at the site.

B. Electric Load

This design allows a Renewable Energy Power Plant (REPP) to operate strategically, which serves the hydrogen requirements and also the electricity demanded for the station [12]. The former was presented through the electrical consumption pattern illustrated in Figure 4, reflecting peaks in consumption, which equaled to 5 kWh between 6 and 9 o'clock in the morning, and have been computed at 71 kWh for the overall daily average demand [13].

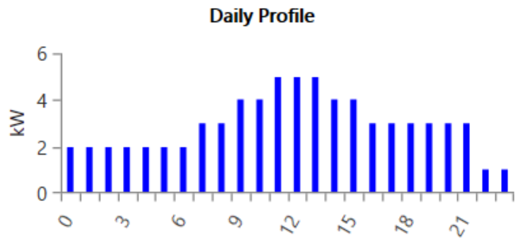

Fig. 4. Electric load profile.

C. Hydrogen Load

The major role of the REPP design is to make sure that there is stable hydrogen production, which is enough for FCVs' refueling in the targeted rural locale. Preliminary assessments have ascertained a consistent demand for hydrogen, which averages at 4.17 kg/h. This is simply translated to a daily hydrogen requirement of 100 kg, culminating in an annual green hydrogen output of 36,500 kg, derived purely from the renewable sources available at the site. The above finding is what Figure 5 underscores regarding the role of REPP in fostering sustainable transportation by providing green hydrogen [14].

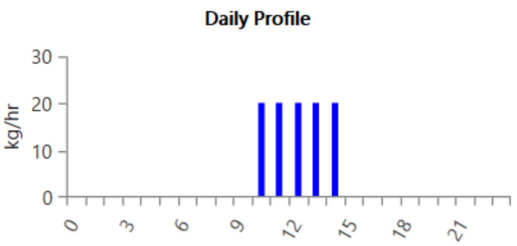

Fig. 5. Hydrogen load profile.

III. DESIGN OF THE STAND ALONE PV/WIND SYSTEM

A. Hybrid System Modeling

Figure 6 represents a schematic of a wind turbine and PV panels for electricity generation in a hybrid energy system. In this system, an inverter is employed to convert the direct current (DC) to an alternating current (AC) of some voltage that will be integrated with electrolyzers for hydrogen production. It also contains a hydrogen storage tank and an infrastructure to consume the hydrogen produced, while its premises have been provided with facilities for an average daily electric power consumption of 71 kWh with a peak load of 5 kW.

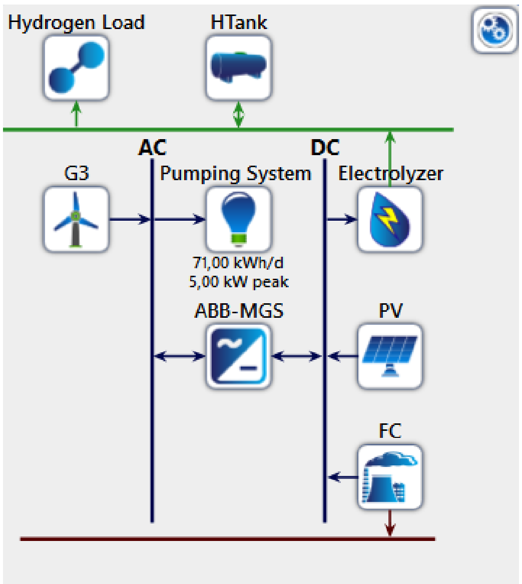

Fig. 6. PV/FC/Wind hybrid system.

B. Operational Control Strategy

In this regard, the economic analysis deals with the LCoH considering the Investment Cost (IC) and the PV station connected to the grid, since hydrogen is produced at the site. LCoH includes the annual total cost in year n, the annual total hydrogen production for year n, and the interest rate. HOMER software enables the simulation of the whole system cost, including the IC, operation cost, and maintenance cost. The Levelized Cost of Energy (LCoE) and LCoH were calculated. The data were introduced to the software and are deployed to certify the numbers of the approximate daily amounts of hydrogen and electric loads projected from the project preliminary planning and used for the wind potential appraisal [16]:

$$LHC = \frac{\sum_{n=1}^{n=25} \left(\frac{TC_n}{(1+i)^n} \right)}{\sum_{n=1}^{n=25} \left(\frac{H_n}{(1+i)^n} \right)} \quad (1)$$

where TC_n is the total cost at year n, H_n is the total hydrogen produced at year n, and i is the interest rate.

The entire proposed renewable energy system for green hydrogen production relies heavily on the ICs. To determine these costs, the HOMER was utilized to simulate the total system cost and calculate LCoE and LCoH. Detailed ICs, maintenance, and operational costs are crucial for optimizing the system, with sizing and costing being integral steps in the process.

In the subsequent section, the software will be further utilized to determine the optimal sizes of electrolyzers and hydrogen storage based on the hydrogen demand. This optimization process ensures that none of the system's components are compromised, as their sizes will be precisely calculated to ensure maximum efficiency and effectiveness. LCoH incorporates the unit costs of all components, annual operating and maintenance costs, component replacement costs, and salvage values. Table I provides detailed financial and component particulars for the standalone system.

TABLE I. TECHNICAL PARAMETERS OF THE STAND-ALONE SYSTEM

Component	Initial cost	Yearly operating cost	Life-time
PV panel	1000 (€/kWp)	10 (€/kWp)	25 (years)
Wind turbine	1200 (€/kW)	50 (€/kW)	20 (years)
FC	750000 (€/kW)	5 (€/kW)	50000 h
Electrolyzer	500 (€/kW)	20 (€/kW)	15 (years)
Hydrogen tank	500 (€/kW)	5 (€/kW)	25 (years)
Power converter	500 (€/kW)	1 (€/kW)	15 (years)

The elements shown in Table I have the following characteristics:

- PV panel: The PV panels, which would operate for up to 25 years, are estimated to cost around €1,000 per kWp. They are associated with modest operational costs, allowing for an extra expense of €10 on an annual basis per kWp.
- Wind turbine: It has an IC of €1200 per kW compared to the PV panels, with a lifespan of 20 years and operating expenses of €50 per kW per year.
- FC: This type of cell can have an operational life of up to 50,000 hours, while, on the other hand, the highest cost of operation amounts is estimated to €750,000 per kW. The annual maintenance cost is €5 per kW.
- Electrolyzer: At a cost of 500 €/kW, and assuming a 15-year lifespan when in operation, with €20/kW/year included for maintenance, it is considered another vital element of hydrogen production equipment.
- Hydrogen tank: The initial setup is valued at €500 per kW, with 25 years of life, and a maintenance cost at €5 per kW per year.
- Power converter: It is essential for the conversion of energy forms and has an IC of €500 per kW, with a lifespan of 15 years at the lowest cost of maintenance per year at €1 per kW.

The aforementioned holistic framework offers a guideline on the financial outlay and operational details to steer towards the economic feasibility and sustainability of a stand-alone PV/Wind system for hydrogen and electricity production in the Tunisian Sahel.

IV. RESULTS AND DISCUSSION

This study utilized HOMER to optimize an off-grid standalone PV/FC-Wind hybrid energy system designed for the Sahel region of Tunisia to meet all-year energy services without interruption. The resulting optimization for these cases is given in Table II, bringing out the system's capacity to respond to the discussed area's energy demands with a complement of solar and wind resources added by the FC technology.

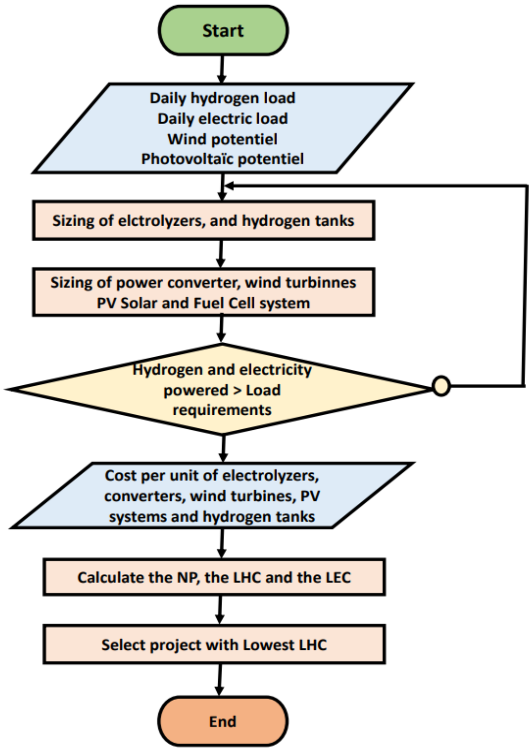

Fig. 7. Flow diagram of the solution's algorithm.

TABLE II. OPTIMIZATION RESULTS OF THE PROPOSED STAND-ALONE SYSTEM

PV (kW)	3092
PEMFC (kW)	3.16
Wind (kW)	270
Power converter (kW)	200
Electrolyzer (kW)	800
Hydrogen tank (kg)	800
Initial capital cost ($)	4438000
Total NPC ($)	5494912.32
CoE ($/kWh)	15.04
Operating cost ($/year)	74990.52

The optimization findings for the hybrid system are:

- PV Contribution: 3092 kW, highlighting solar energy's significant role in the system.
- Proton Exchange Membrane FC (PEMFC): 3.16 kW, illustrating the FC's support in energy conversion.
- Wind energy contribution: 270 kW, showcasing wind as a supplementary energy source.
- Power conversion unit: 200 kW, essential for transitioning between energy forms.
- Electrolyzer capacity: 800 kW, pivotal for hydrogen production.
- Hydrogen storage capacity: 800 kg, underscoring the system's capability for energy storage.

Table II provides the total Net Present Cost (NPC) of the estimated first capital investment, which is around $4,438,000, equivalent to $5,494,912.32, for the amount of money determining how much is required to be invested for the system implementation.

Figure 8 recapitulates the proposed stand-alone hybrid energy system and the financial costs.

With an operating cost amounting to $74,990.52 per year, the Cost of Energy (CoE) describes how efficient the operations and subsequently the cost-effective nature of the system are. A careful assessment of electricity production (Figure 9) evidences that the total sum from both the PV and wind components gives 90.1% of the total energy produced, hence proving its dominance in the energy mix.

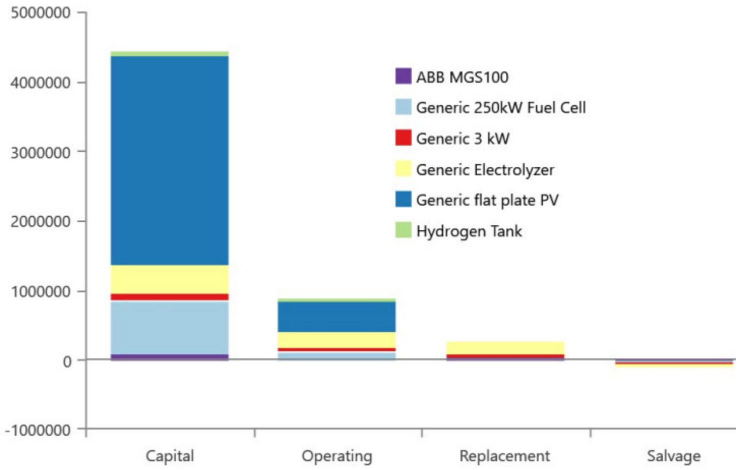

Fig. 8. PV/FC/Wind hybrid system.

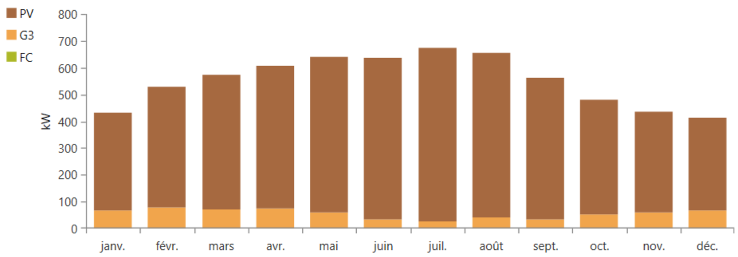

Fig. 9. Monthly average electricity production for the PV wind FC system.

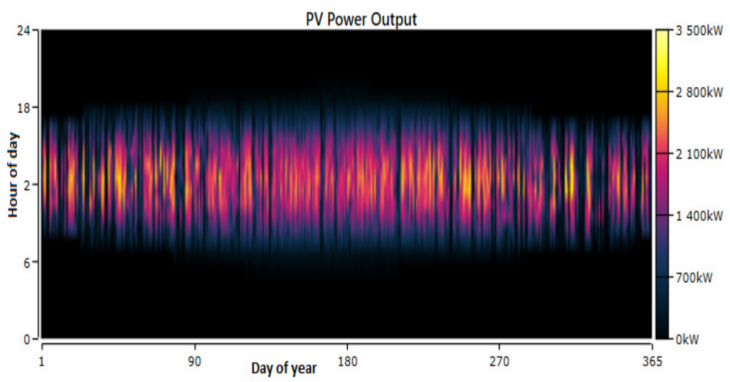

Fig. 10. Annual PV generator operation.

Operational performance views (Figures 10–12) reveal the functionality of the system with different components. Efficient conversion of the solar power into green hydrogen indicates that hydrogen production is pegged between 9 am and 5 pm, i.e. during peak sunlight hours. So, prudently, about 180 tons of green hydrogen are being produced in a year from 1,723,960 kWh of solar power, ensuring that the electrolyzers are at work but not crossing the limit of 800 kW.

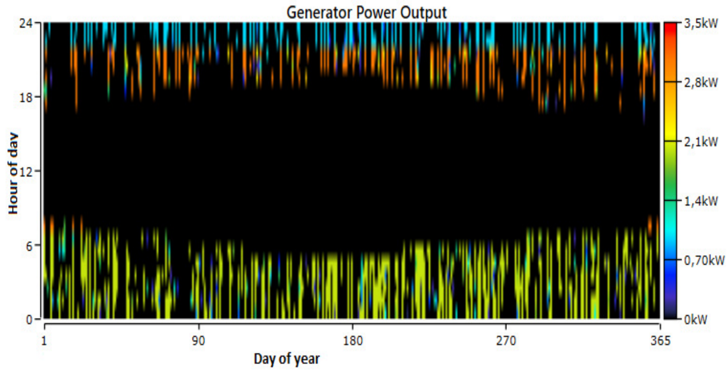

Fig. 11. Annual PEMFC generator operation.

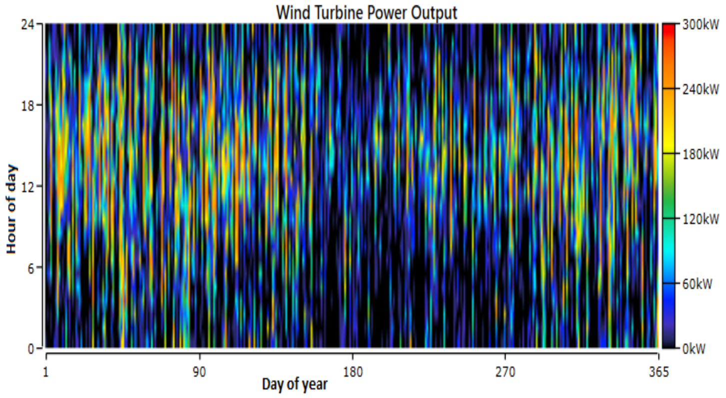

Fig. 12. Annual wind turbine generator operation.

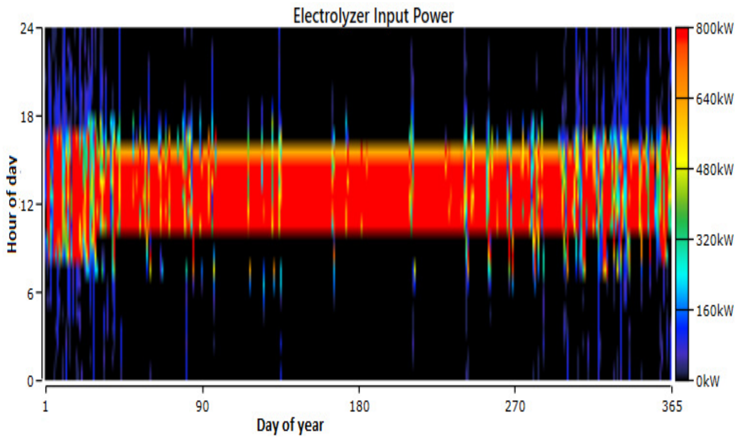

Fig. 13. Variation of the electricity consumed by the electrolyzer.

These findings validate that the varied and consistent energy needs of the Sahel region can be met by renewable energy sources in a cost-effective and ecologically conscious manner.

V. CONCLUSION

This research brings on board a robust hybrid energy system, designed to solve the electricity demand of the Hergla-Sousse region of the Tunisian Sahel without any form of battery storage. The system architecture includes a wind turbine, Fuel Cells (FCs), Photovoltaic (PV) panels, and an electrolyzer, as well as an inverter and storage tanks for hydrogen. The system performance analysis has disclosed that with the combination of wind, FC, and PV, the Levelized Cost of Hydrogen (LCH) and Net Present Cost (NPC) values were relatively high. The factors for this increase were the significant investment costs at the initial stages of the system's implementation associated with FC technology. One big challenge, however, to this hybrid system, even though it is very promising in potential, would be the initial financial investment in the development of the infrastructure for green hydrogen.

The current research also allows for analyzing the environmental problem related to the current production processes of PV panels, wind turbines, and parts of other systems. The processes are mostly based on non-renewable energy resources that contribute to the production of greenhouse gases and other further pollution of the environment. So, while this hybrid system introduces a possibility in the sustainable generation of energy, it also insinuates the need for progression in manufacturing practices towards minimizing the environmental footprints and strengthening the sustainability of the system as a whole.

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