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POWER SYSTEMS AND POWER ELECTRONICS

Modeling, analysis, and techno-economic assessment of a clean power conversion system with green hydrogen production

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Abstract. The power sector confronts a crucial challenge in identifying sustainable and environmentally friendly energy carriers, with hydrogen emerging as a promising solution. This paper focuses on the modeling, analysis, and techno-economic evaluation of an independent photovoltaic (PV) system. The system is specifically designed to power industrial loads while simultaneously producing green hydrogen through water electrolysis. The emphasis is on utilizing renewable sources to generate hydrogen, particularly for fueling hydrogen-based cars. The study, conducted in Skikda, Algeria, involves a case study with thirty-two cars, each equipped with a 5 kg hydrogen storage tank. Employing an integrated approach that incorporates modeling, simulation, and optimization, the techno-economic analysis indicates that the proposed system provides a competitive, cost-effective, and environmentally friendly solution, with a rate of 0.239 $/kWh. The examined standalone PV system yields 24.5 GWh/year of electrical energy and produces 7584 kg/year of hydrogen. The findings highlight the potential of the proposed system to address the challenges in the power sector, offering a sustainable and efficient solution for both electricity generation and hydrogen production.

Keywords: green hydrogen; PV systems; electrolysis; energy conversion; techno-economic; optimization.

1. INTRODUCTION

The current situation and future projections indicate that fossil fuel availability is not guaranteed for a long time. As a result, there is a critical need for an alternative fuel that is derived mostly from renewable resources and is used in an environmentally benign manner. Nowadays, renewable energy sources (RESs) have become an attractive alternative to conventional energy sources [1]. Environmental concerns, the depletion of conventional sources, and global warming play an important role in accelerating this transition [2]. RESs are available freely and are environmentally friendly.

Hydrogen can help with the resolution of various energy challenges. It is more efficient than gasoline in terms of converting energy to movement [3]. In addition to improved efficiency, hydrogen emits fewer pollutants into the atmosphere than traditional fossil fuels [4, 5]. When hydrogen is combusted, it produces clean water; hence it is considered a clean fuel [6–8].

In numerous countries, hydrogen is highlighted as a critical avenue for deep decarbonization in the energy and transportation sectors [9]. Hydrogen is a versatile energy vector that can be produced from a variety of renewable and non-renewable sources. Non-renewable resources account for 96% of hydrogen production technologies, with natural gas accounting for 48%, followed by the gasification of coal and oil accounting for 18% and 30%, respectively [10]. However, the use of RES seems an ideal way to replace fossil fuels and decarbonize some sectors [11].

Green hydrogen is produced based on RESs, mainly photovoltaic (PV) systems.

Water is an important agent in the different proven ways of solar hydrogen synthesis, as the separation of water creates oxygen and hydrogen [12, 13]. Furthermore, water and sunlight are abundant on Earth. This increases the dependability of the solar-powered water-splitting technology [14].

Due to its high calorific value, energy density, and minimal or near-zero emissions, hydrogen production based on water electrolysis is now one of the most common solutions for storing chemical energy [15].

Power to hydrogen to power (P2H2P) is a novel concept that might be a potential option to store and provide power when needed [3].

The optimal design of these systems is an important point in the study of the feasibility of hydrogen production. The optimal design of PV-electrolyzer systems is studied in the literature. Kouhili *et al.* [15] developed a sustainable energy model using renewable sources to produce hydrogen, based on information obtained from three pilot plants. Tebibel *et al.* investigated the production of green hydrogen via the electrolysis process using a PV system [16]. The authors developed a semi-empirical relationship between power consumption and the rate of hydrogen production. Furthermore, an optimal management strategy for power and hydrogen is proposed to increase the system efficiency. The authors in [17] reported a techno-economic analysis of two PV-hydrogen production systems, namely photoelectrochemical and PV-electrolysis, to determine the more viable tech-

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nique based on the levelized cost of hydrogen (LCOH). Boudries & Khellaf carried out a techno-economic assessment of hydrogen production processes driven by solar and nuclear energies. The analysis aimed to assess which technique is economically competitive for the production and delivery of hydrogen [18]. Ramadan [19] presented a review to shed light on fully green systems that include both green sources and green storage. As an example, the author discusses the various solar hydrogen coupling technologies such as PV-hydrogen systems. Basu *et al.* used HOMER® software to simulate three combinations of renewable energy sources focusing on hydrogen storage problems [20].

Boucenna *et al.* conducted a financial viability analysis of an off-grid hybrid renewable system designed to provide electricity to multiple campuses of the University of Skikda in Algeria. The study employed the HOMER software for system optimization and simulation [21]. However, the authors, while focusing on the feasibility of the hybrid system, did not explore the potential of meeting the energy demands of the proposed load through a singular renewable source.

Messaoudi *et al.* analyzed wind resource availability by examining meteorological data, with a focus on identifying the wind resource potential in specific geographic locations. Through this investigation, the research revealed substantial wind energy potential in Algeria [22]. The findings underscored the country's capability for harnessing wind power, particularly for hydrogen production. Notably, it is important to highlight that, in this paper, the consideration of photovoltaic (PV) to hydrogen conversion was omitted, emphasizing the exclusive focus on wind as a driving force for hydrogen production. Zegueur *et al.* assessed in [23] an eco-friendly power supply for a rural telecom station in Skikda, Algeria, proposing a hybrid PV-wind system with diesel generators and batteries. Various configurations were studied, and HOMER PRO software identified a 5-kW diesel generator, 3.81 kW PV, three wind turbines, and a 14-battery bank as the optimal design. Nevertheless, the suggested optimal solution lacks environmental sustainability due to its inclusion of a diesel engine. Ram *et al.* investigate the viability of hydrogen production for fuel cell buses in Fiji in their study [24]. The research primarily centers on dimensioning hybrid microgrids, incorporating solar panels and wind turbines as the main energy sources for hydrogen generation, taking into account scenarios involving both off-grid and grid-connected setups. However, it is noteworthy that the investigation emphasizes the feasibility of hybrid sources, placing a particular emphasis on sources beyond solely solar power.

The broader problem addressed in this research pertains to the urgent and overarching challenges faced by the global power sector in the quest for sustainable and environmentally friendly energy solutions. As societies grapple with the consequences of climate change, the depletion of conventional energy sources, and the environmental impacts of traditional power generation, there is a critical need to transition towards cleaner, renewable alternatives. The research zooms in on the specific dilemma of finding new and inexhaustible energy carriers, particularly in light of the uncertainty surrounding the long-term availability of fossil fuels. This broader problem encompasses the necessity for transformative shifts in energy production methods to mitigate environmental degradation, reduce greenhouse gas emissions, and ensure a resilient and sustainable energy future. The focus on green hydrogen production through the integration of advanced technologies like photovoltaic systems represents a strategic response to this broader problem, aiming to create a paradigm shift in the power sector towards more efficient, economically viable, and environmentally friendly energy solutions. The research thus contributes to the ongoing global discourse on addressing the energy trilemma of security, sustainability, and affordability, seeking to propel the transition towards a cleaner and more resilient energy landscape.

The current study focuses on the optimal design of an electric energy and hydrogen energy conversion station energized by the solar PV system. A techno-economic analysis of PV-hydrogen generation via the water electrolysis process was carried out. The system under study is intended to feed an electric industrial load and the excess of the electric energy to produce the amount of hydrogen required to refuel hydrogen cars in the region of Skikda, Algeria. The main objective is to produce the highest possible amount of electricity and hydrogen with the minimum cost, and with negligible environmental effects.

The main objective of the research is the use of PV systems to produce electricity and hydrogen and the optimization of the conversion system to maximize the amounts of electric energy and hydrogen with the lowest levelized cost of energy (LCOE).

This research is crucial for multiple reasons. Firstly, it addresses the imperative need in the power sector to discover new, sustainable, and environmentally friendly energy sources, particularly as the availability of fossil fuels becomes uncertain in the long term. Secondly, the study underscores the significance of utilizing renewable energy sources (RESs) to combat environmental concerns, depletion of conventional sources, and the impacts of global warming. The focus on green hydrogen, produced from RESs like photovoltaic (PV) systems, introduces a cleaner and more sustainable method for hydrogen generation, contributing to ongoing technological advancements in clean energy. Moreover, the research highlights the versatility of hydrogen as an energy vector, emphasizing its potential to replace fossil fuels and decarbonize specific sectors. The techno-economic evaluation conducted in the study is pivotal for demonstrating the economic viability of the proposed clean power system, emphasizing its competitiveness, cost-effectiveness, and environmental friendliness, thereby promoting widespread adoption. Additionally, the research localized examination of Skikda, Algeria, offers a region-specific perspective, considering local factors and contributing valuable insights to the development of tailored sustainable energy practices for specific geographic locations.

Specific innovations and unique methodologies employed in the study include the integration of photovoltaic (PV) systems with electrolysis for green hydrogen production, addressing both industrial loads and refueling of hydrogen-based cars. The multi-objective optimization approach considers maximizing converted electric energy and hydrogen production while minimizing costs. The localized case study in Skikda, Algeria, offers region-specific insights, acknowledging geographic and environmental factors. The comprehensive analysis covers system component modeling, techno-economic evaluation, and optimization techniques. Additionally, the study emphasizes the practical application of green hydrogen as an energy carrier for transportation, contributing to the discourse on sustainable energy solutions.

The rest of the paper is organized as follows: The electrolysis process used to produce hydrogen is described in Section 2, while Section 3 presents the system component modeling. Section 4 describes the methodology used to conduct the research. Section 5 discusses the formulation of the optimization problem, and Section 6 discusses the result of the simulation and optimization. The final section is a conclusion to the research.

2. THEORY

Despite its abundance, hydrogen is most commonly found in combination with other elements, such as oxygen and carbon, necessitating its production.

Hydrogen exhibits various physical states – gas, solid, or liquid – depending on the prevailing temperature and pressure conditions. Under standard conditions of 25°C temperature and 1 bar pressure, hydrogen manifests as a diatomic gas with a density of 0.089 kg/m^3. However, at extremely low temperatures below −262°C, hydrogen transitions into a solid state, with a density of 70.6 kg/m^3. In its liquid state, hydrogen occupies a narrow range between its triple point and critical point, yielding a density of 70.8 kg/m^3 at approximately −253°C [25–27].

One notable characteristic of hydrogen is its exceptional gravimetric density, estimated to be approximately 120 MJ/kg. This high energy content means that, by mass, hydrogen possesses nearly three times the energy content of gasoline, which typically contains around 44 MJ/kg. In terms of usable energy, hydrogen boasts 33.6 kWh per kg, compared to only 12.2 kWh per kg for gasoline and up to 14 kWh per kg for diesel [25]. However, when considering volumetric density, hydrogen lags behind other fuel sources, presenting lower volumetric energy density [25].

Among various processes, water splitting is the most developed, sustainable, and non-polluting process.

The separation of elements by running a direct current through a composite substance is known as electrolysis. Water can be split into hydrogen and oxygen via electrolysis.

The electric energy converted by the PV system feeds an electrolyzer used to dissociate water molecules according to the following chemical reaction (1):

$$2H_2O \longrightarrow 2H_2 + 0_2\,. \tag{1}$$

PV panels convert sunlight into electricity. To drive the converted energy from the panels to the electrolyzer, other components are required, namely the charge controller, static power converter, and storage systems.

3. GOVERNING EQUATIONS

Figure 1 depicts the proposed system, which consists of a PV array, a battery bank, an electrolyzer, a hydrogen storage tank, and a converter.

3.1. Solar PV

PV panels are made up of multiple separate cells that are linked together in series, parallel, or a mix of the two types. They use the PV effect to produce electricity from the sunlight [28, 29]. A variety of factors influence the amount of energy that a PV panel converts over time. The most important variables are the panel area, the peak power, and the irradiance, which is affected by the season, location, number of hours of sunshine, and meteorological conditions. The following equation (2) can

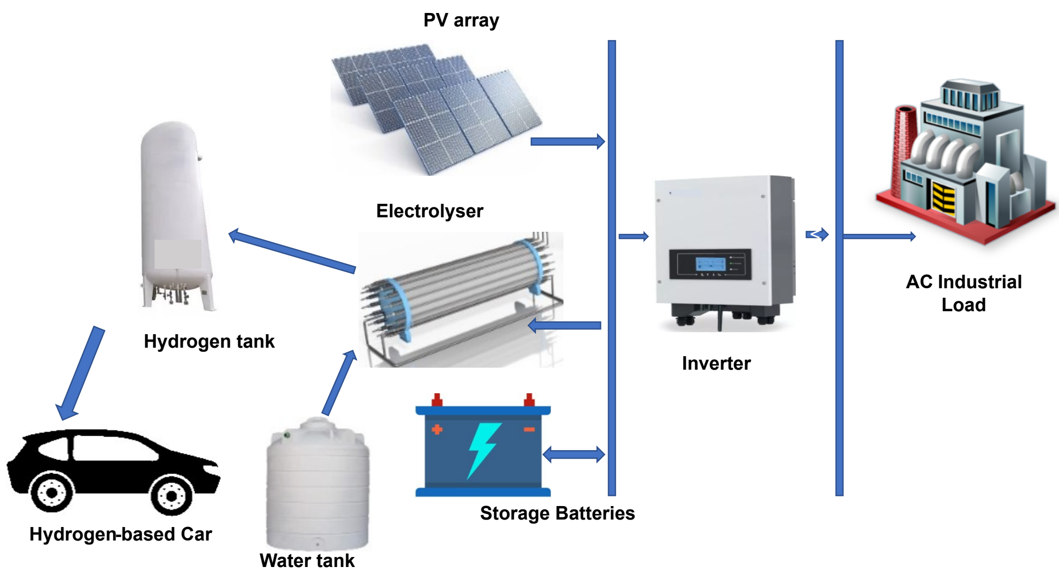

Fig. 1. The architecture of the proposed system

be used to calculate the amount of energy converted by a PV panel [30, 31]:

$$P_{PV} = \eta_{PV,STC}\left[1+\frac{\mu}{\eta_{PV,STC}}(T_a - T_{STC}) + \frac{\mu}{\eta_{PV,STC}}\frac{9.5}{5.7+3.8v}\frac{(NOCT-20)}{800} \times (1-\eta_{PV,STC})G_{g,t}\right]A_{PV}G_{g,t}, \tag{2}$$

where P_{PV} denotes the power delivered by the PV panel (W); STC denotes the standard test conditions; $\eta_{PV,STC}$ is the panel's efficiency under STC (%); μ is the temperature coefficient (%/°C); v is the wind speed (m/s); A_{PV} is the area of the panel (m^2); T_a is the ambient temperature; T_{STC} is the temperature at STC; $NOCT$ is the nominal operating cell temperature; $G_{g,t}$ is the instantaneous global irradiance.

3.2. Electrolyzer and storage tank

The electrolyzer operates through the electrolysis process, which involves the flow of electricity from one electrode to another and the breakdown of water into oxygen and hydrogen. In the majority of studies, the output of the electrolyzer is perfectly connected to a hydrogen storage tank [32, 33].

The power received at the hydrogen tank is transferred by the electrolyzer and is estimated according to (3):

$$P_{\text{elec\_tank}} = \eta_{\text{elec}} P_{\text{ren\_elec}}, \tag{3}$$

where $P_{\text{elec\_tank}}$ is the power transferred from the electrolyzer to the hydrogen tank; $P_{\text{ren\_elec}}$ is the power transferred from the PV system to the electrolyzer; η_{elec} is the efficiency of the electrolyzer.

The mass of the stored hydrogen is estimated in (4) as [20]:

$$m_{\text{tank}}(t) = E_{\text{tank}}/HHV_{H_2}, \tag{4}$$

where HHV_{H_2} is the hydrogen higher-heating value, taken as 38.9 kWh/kg [32]; E_{tank} is the output energy stored in the tank, and is estimated by (5) as:

$$E_{\text{tank}}(t) = E_{\text{tank}}(t-1) + \left[P_{\text{elec\_tank}}(t) - \left(P_{\text{load}}(t)/\eta_{\text{storage}}\right)\right]. \tag{5}$$

$P_{\text{load}}(t)$ is the power consumed by the load; η_{storage} is the efficiency of the hydrogen storage tank, estimated as 95% [34].

3.3. Battery

The number of batteries connected and the state of each battery at any given time determine the amount of energy produced and consumed. When the battery is charged, power generation exceeds load demand. Then equation (6) is used to calculate the amount of power available in the battery bank at any given time [35].

$$E_{\text{batt}}(t) = E_{\text{batt}}(t-1) + \eta_{CC}\eta_{BCH}E_{\text{extra}}(t), \tag{6}$$

where $E_{\text{extra}}(t)$ is the extra energy generated by the PV system; η_{CC} is the efficiency of the charge controller, and η_{BCH} represents the battery charging efficiency.

3.4. Converter

The system requires a converter to maintain the energy flow between the DC and AC buses. Its main function is to regulate the flow of current to the AC load. The converter is characterized by the conversion efficiency and the rated power, and can be calculated by (7) [34]:

$$\eta_{\text{conv}} = \frac{P_{\text{conv, out}}}{P_{\text{conv, in}}} \tag{7}$$

where η_{conv} is the converter efficiency; $P_{\text{conv, in}}$ is the power received by the converter, and $P_{\text{conv, out}}$ is the power delivered by the converter.

3.5. Load

The optimal sizing of system components is based on two types of loads, an AC industrial load depicted in Fig. 2, and a hydrogen load depicted in Fig. 3. The average energy consumed by the electric load is assumed to be 24 000 kWh/day. The hydrogen load is produced to feed hydrogen-based cars. The average amount of hydrogen required is about 20 kg/day with a peak of 2 kg/hour (Fig. 3).

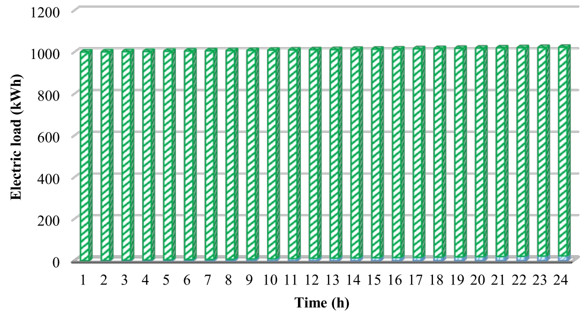

Fig. 2. Daily AC load profile

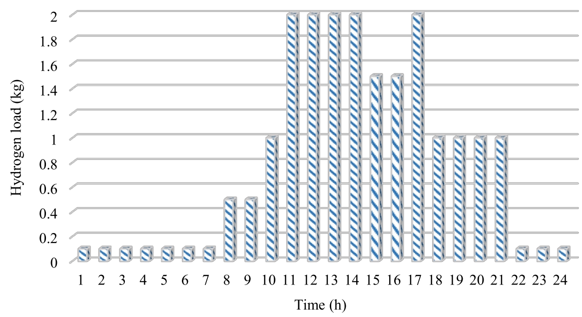

Fig. 3. Daily hydrogen load profile

4. METHODOLOGY

The study aims to conduct a techno-economic analysis of the PV-based power system. The amount of converted electric energy is required to feed an industrial AC load. The surplus energy is used to feed an electrolyzer which produces hydrogen via water splitting. The hydrogen produced is required to refuel 32 cars daily. Each car has a 5 kg hydrogen tank. The methodology followed for the study is depicted in Fig. 4.

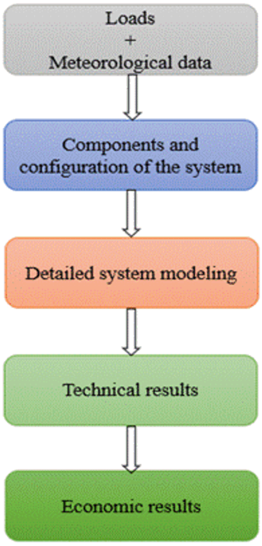

Fig. 4. 4. Simulation steps

5. OPTIMIZATION PROBLEM FORMULATION

The multi-objective optimization problem aims to maximize the converted electric energy and the amount of hydrogen produced while minimizing the electric and hydrogen costs. The problem can be mathematically formulated as follows (8):

$$\begin{cases} \text{Max}\left(P_{PV}, M_{H_2}\right) \\ \text{Min}(LCOE) \\ \text{Subject to :} \\ \quad P_{PV}\ (\text{kW}) \geq P_{\text{load}} + P_{\text{electrolyzer}} \\ \quad P_{PV},\ N_{\text{batt}},\ P_{\text{conv}},\ P_{\text{electrolyzer}},\ V_{\text{tank}} > 0, \\ \quad N_{\text{batt}}\ \text{integer}, \end{cases} \tag{8}$$

where P_{PV} is power converted by PV array (kWh); N_{batt} is the number of batteries; P_{conv} is the converter capacity (kW); $P_{\text{electrolyzer}}$ is the electrolyzer capacity (kW); V_{tank} is the hydrogen tank capacity (kg).

6. RESULTS AND DISCUSSION

In this study, standalone energy system components were meticulously selected and sized based on input data such as electric and hydrogen loads, renewable sources, techno-economic details for all system components, dispatch strategy, and constraints. The power system was optimally sized to meet the specified loads, considering the net present cost (NPC) estimated through equation (9) [36]:

$$NPC = CC_{\text{Syst}} + RC_{\text{Syst}} + O\ \ \&\ \ MC_{\text{Syst}}, \tag{9}$$

where CCSyst is the capital cost of the system and is calculated as the sum of the capital cost of all subsystems; RCSyst is the replacement cost of the system and is calculated as the sum of the replacement costs of all system components; O&MCSyst is defined as the operating and maintenance cost of the overall system and is estimated by adding the O&M of all system components.

At the outset, the geographical coordinates, specifically the longitude and latitude, of the designated area were utilized to retrieve essential meteorological data. This data retrieval process involved accessing information from the NASA Surface Meteorology and Solar Energy database [37]. These data consist of monthly averaged values spanning 22 years and are visualized in Fig. 5.

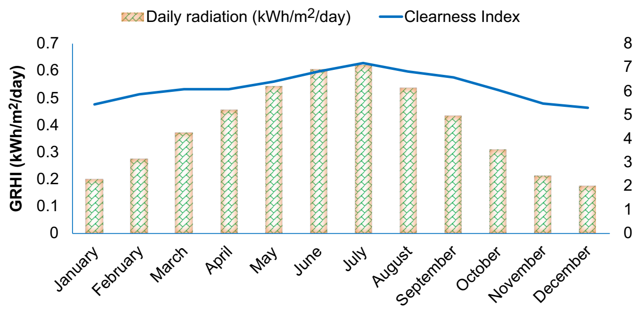

Fig. 5. Monthly average Solar Global Horizontal Irradiance (SGHI) and Clearness Index Data [37]

Numerous system configurations underwent simulation to identify feasible solutions adhering to predefined constraints. Calculations were meticulously executed for each 60-minute simulation time step, culminating in a comprehensive annual total of 8760 simulations. The intricate process involved extensive simulations and optimizations to compute the energy production and delivery. An optimization study was then conducted to determine the optimal design of the power system, considering specified limitations and minimizing the net present cost (NPC).

The optimized system configuration, derived from a multi-objective analysis based on the cost of electricity (COE), comprises a 15.573 MW PV array, 40 172 storage batteries, a 400 kW electrolyzer, a hydrogen storage tank with a 120 kg capacity, and a 1.861 MW converter. The PV array, with a rated capacity of 15.573 MW, exhibits a mean output of 2.786 MW and a maximum output of 16.835 MW, yielding a total annual production of 24.4 GW. The battery bank, consisting of 40 172 batteries, each arranged in strings of four, amounts to 125.437 MW nominal capacity with 75.3 hours of autonomy. The bi-directional converter, rated at 1861 kW, operates with a mean power of 999 kW, a maximum output of 1833 kW, and a 53.7% capacity factor. The electrolyzer, with a 400 kW capacity, generates hydrogen at a mean output of 0.874 kg/hr and a maximum output of 8.62 kg/hr. The total hydrogen production is 7657 kg/year, requiring 46.4 kWh/kg. The hydrogen tank, storing 120 kg, has an energy capacity of 4000 kWh, providing four hours of autonomy. The system, depicted in Fig. 6, converts electrical energy through the PV system to fulfill 96.1% of the AC industrial load, resulting in minimal unmet electric load (0.057%), capacity shortage (0.08%), and electrolyzer energy needs (1.53%). System power losses are at 1.98%, totaling 460 787 kWh/year.

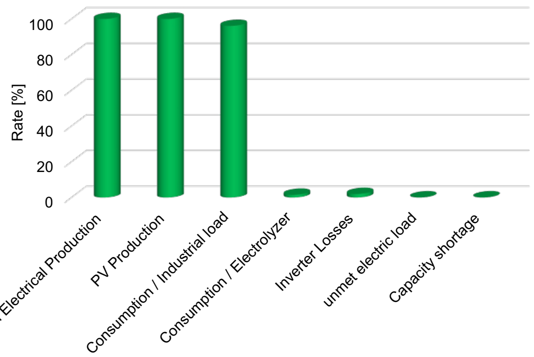

Fig. 6. System electrical production

The data presented in Fig. 6 illustrates a substantial solar global horizontal irradiance (SGHI) in the area, ranging from a minimum of 2.01 kWh/m^2/day in December to a maximum of 7.08 kWh/m^2/day in July.

Subsequently, system components are carefully chosen, and parameters for electric and hydrogen loads are established. Following the provision of technical and economic details for the system components (refer to Table 1) and the definition of optimization constraints, the simulation is executed.

The electrolyzer converts the total hydrogen production of 7657 kg/year to meet a hydrogen load of 7584 kg/year. Figure 7 summarizes the total net present cost (TNPC) at $26 993 685.50 and a levelized cost of energy of 0.239 $/kWh. The TNPC breakdown reveals that 62% is attributed to the total capital cost of system components (approximately $19 million), 20% to the replacement costs (around $6.3 million), 12% to the operation and maintenance (O&M) costs (about $3.6 million), and the remaining 7% to the salvage rate (equivalent to $2 million).

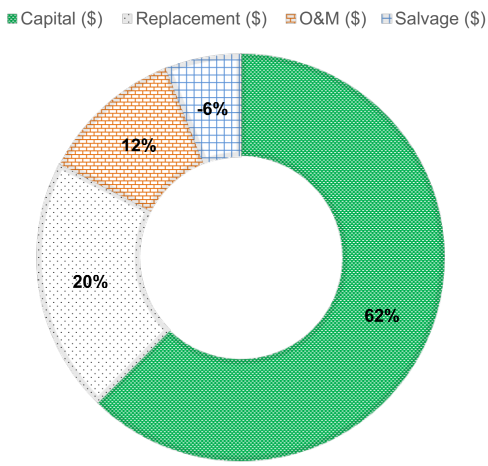

Fig. 7. Total NPC of the optimized system

Figure 8 provides a breakdown of the net present cost (NPC) for each sub-system. The storage system stands out with a total cost of approximately $14.85 million, constituting 55% of the total net present cost (TNPC). The PV array has an NPC of around $11.27 million, representing 41.75% of the TNPC. The NPC of the inverter amounts to $740 798.97, accounting for 2.74% of the TNPC. In contrast, the NPC of the electrolyzer and the hydrogen tank are negligible, each with a rate of less than 1%, amounting to $95 144.9 and $27 513.02, respectively.

Table 1
Technical and economic specifications

Component	Technical specifications	Economic specifications
PV panel	Type: Sun power X21-335-350W-BLK; Module technology: monocrystalline Nominal maximum power ($P_{\max}$ = 350 W); Operating voltage V_{mp} = 57.3 V Operating current imp = 5.85 A; Open circuit voltage VOC = 67.9 V; Short circuit current ISC = 6.23 A; Efficiency = 21%; Nominal operating cell temperature (NOCT) 43°C; Derating factor fPV = 88%, Lifetime = 25 years	Capital cost = $685/kW Replacement cost = $0/kW Operation and maintenance cost (O&M) = $3/year/kW
Storage battery	Type: Surrette S-260; Technology: deep-cycle flooded lead-acid Max capacity: 260 Ah; Nominal voltage: 12 V	Capital cost = $200 Replacement cost = $200 O&M = $5/year
Electrolyzer*	Type: Generic electrolyzer (DC); Efficiency ηEZ = 90%, Lifetime = 15 years	Capital = $100/kW Replacement = $100/kW O&M = $8/year/kW
Hydrogen tank*	Lifetime = 25 years	Capital = $0.5/kg Replacement = $100 O&M = $10/year/kg Hydrogen fuel cost = $1/kg
Converter (inverter)*	Type: Leonics S219CPH; Voltage = 48 VDC; Efficiency = 96%; Lifetime = 25 years	Capital = $40/kW Replacement = $40/kW O&M = $10/year/kW

* Data taken from [35]

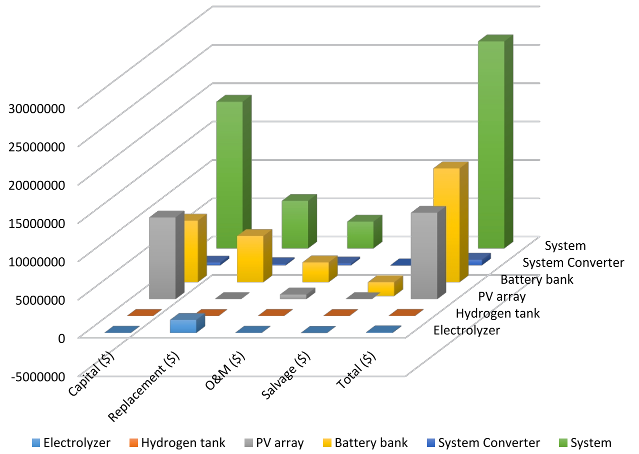

Fig. 8. NPC of system components

7. CONCLUSIONS

In conclusion, this research represents a significant contribution to multiple domains within electrical engineering, including power systems, power electronics, industrial electronics, power quality, and modern information and energy technologies. By offering a comprehensive analysis and innovative solutions in the realm of clean energy production and hydrogen utilization, this study advances the discourse on sustainable energy practices.

The optimized design of the off-grid energy system, integrating photovoltaic (PV) systems, electrolyzers, battery banks, and converters, not only demonstrates its efficacy in meeting the electricity needs of an industrial load but also showcases its capability to produce green hydrogen simultaneously. This innovative approach has far-reaching implications, particularly in regions like Skikda, Algeria, where localized implementation of sustainable energy solutions is essential, considering geographic and environmental factors specific to the area.

Beyond the technical advancements, the impact of the study extends to various disciplines within electrical engineering. In power systems, the model presented for an efficient, reliable, and sustainable off-grid power system sets a precedent for the widespread adoption of similar configurations, thereby contributing to global efforts to transition towards renewable energy sources. The integration of components such as PV systems and converters in power electronics underscores technological advancements and pushes the boundaries of clean energy conversion.

Moreover, the practical implications of the proposed system in meeting industrial energy demands highlight its relevance in industrial electronics. However, it is crucial to acknowledge potential challenges associated with scalability, economic viability, regulatory frameworks, and societal acceptance. Addressing these challenges will be pivotal in ensuring the successful implementation and widespread adoption of clean energy solutions.

Furthermore, the techno-economic evaluation of the proposed system emphasizes its competitive, economical, and environmentally friendly attributes, thereby addressing key aspects of power quality. The utilization of green hydrogen as an energy carrier aligns with the evolving landscape of modern information and energy technologies, offering a sustainable alternative to traditional fossil fuels and contributing to global efforts to reduce carbon emissions.

In essence, this research bridges the gap between various domains within electrical engineering and lays the groundwork for transformative advancements in the integration of renewable energy sources and sustainable energy practices. Moving forward, further discussion on the implications of the results, potential challenges, and avenues for future research will be essential in maximizing the impact of this study and shaping the future of clean energy technologies. This paper serves as a catalyst for ongoing dialogue and action towards a more sustainable and environmentally friendly energy landscape.

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