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Optimizing a Sustainable Power System with Green Hydrogen Energy Storage for Telecommunication Station Loads

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ABSTRACT

Telecommunication stations situated in rural areas often rely on diesel generators as their primary energy source to meet electricity demand, given the absence of a power grid. However, this heavy dependence on diesel generators leads to escalated operational and maintenance expenses, while exacerbating global warming through greenhouse gas emissions. This paper proposes a shift towards a 100% hybrid renewable energy system integrated with hydrogen energy storage as a sustainable alternative. The proposed system incorporates photovoltaic (PV) panels, wind turbines, an electrolyzer, a fuel cell, a hydrogen tank, and a converter.

Using HOMER Pro software, the optimal sizing of the system was determined, resulting in a configuration with 12.3 kW PV capacity, two 10 kW wind turbines, a 10kW fuel cell, a 20 kW electrolyzer, a 5 kg hydrogen tank, and a 17.3 kW converter. This configuration achieved a net present cost (NPC) of \$155,705 and a cost of energy (COE) of \$0.388/kWh, offering substantial cost-effectiveness. Compared to the base case relying solely on diesel generators, the system could avoid approximately 31,081 kg of CO_2 emissions annually. Finally, a sensitivity analysis was conducted to assess the impact of meteorological variations on the system's economic outputs. The findings of this comprehensive study demonstrate the proposed hybrid system's feasibility in terms of both environmental sustainability and economic viability, presenting a sustainable alternative for off-grid telecommunication stations.

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تحسين نظام طاقة مستدام مع تخزين طاقة الهيدروجين الأخضر لأحمال محطات الاتصالات

أحلام زقار، توفيق سباغ، عبد الرزاق مطاطلة.

ملخص: غالباً ما تعتمد محطات الاتصالات السلكية واللاسلكية الواقعة في المناطق الريفية على مولدات الديزل كمصدر رئيسي للطاقة لتلبية الطلب على الكهرباء، نظراً لعدم وجود شبكة كهرباء. ومع ذلك، فإن هذا الاعتماد الكبير على مولدات الديزل يؤدي إلى تصاعد نفقات التشغيل والصيانة، مع تفاقم ظاهرة الاحتباس الحراري من خلال انبعاثات الغازات المسببة للاحتباس الحراري. تقترح هذه الورقة البحثية التحول نحو نظام هجين للطاقة المتجددة بنسبة 100% مدمج مع تخزين الطاقة الهيدروجينية كبديل مستدام. يشتمل النظام المقترح على ألواح كهروضوئية وتوربينات رياح ومحلل كهربائي وخلية وقود وخزان هيدروجين. من خلال استخدام برنامج HOMER Pro، تم تحديد الحجم الأمثل للنظام، مما أدى إلى تكوين بسعة 12.3 كيلو وات من الطاقة الكهروضوئية، واثنين من توربينات الرياح بقدرة 10 كيلو وات، وخلية وقود بقدرة 10 كيلو وات، ومحلل كهربائي بقدرة 20 كيلو وات، وخزان هيدروجين سعة 5 كجم، ومحول بقدرة 17.3 كيلو وات. حقق هذا التكوين تكلفة صافية حالية (NPC) قدرها 155705 دولارًا وتكلفة طاقة (COE) قدرها 0.388 دولارًا لكل كيلو واط ساعي، مما يوفر فعالية كبيرة من حيث التكلفة. وبالمقارنة مع الحالة الأساسية التي تعتمد فقط على مولدات الديزل، يمكن للنظام تجنب ما يقرب من 31081 كجم من انبعاثات ثاني أكسيد الكربون سنويًا. أخيرا، تم إجراء تحليل للحساسية لتقييم تأثير التغيرات الجوية على المخرجات الاقتصادية للنظام. وتوضح نتائج هذه الدراسة الشاملة جدوى النظام الهجين المقترح من حيث الاستدامة البيئية والجدوى الاقتصادية، مما يوفر بديلاً مستدامًا لمحطات الاتصالات البعيدة .

الكلمات المفتاحية – طاقة متجددة، الاتصالات، تحسين، بيئة، هيدروجين أخضر.

1. INTRODUCTION

The surge in population expansion and industrial advancement has led to a rise in energy usage across various sectors, including telecommunications [1]. Recent estimations suggest that there are approximately 321,000 off-grid Radio Base Stations (RBSs) currently in operation, with projections indicating a potential growth of about 22% in the foreseeable future. Moreover, there are ongoing initiatives for the implementation of 5G technology in the coming years [2].

Many telecommunication stations situated in rural and isolated regions heavily depend on diesel generators (DGs) to maintain their operations, as they lack access to the utility grid or find grid extensions financially burdensome. Despite appearing economically advantageous initially, DGs pose significant operational challenges. They incur high maintenance costs and consume substantial amounts of fuel, leading to elevated operating expenses due to the continuous rise in fossil fuel prices. Moreover, their usage contributes to environmental degradation, with substantial greenhouse gas emissions exacerbating the threat of global warming [3], [4], [5]. Furthermore, DGs exhibit relatively low efficiency, typically around 30% [6], [7]. Therefore, it is crucial to explore alternative power solutions that prioritize reliability, cost-effectiveness, and environmental sustainability.

Renewable energy sources like solar and wind power are widely recognized as pivotal in decarbonizing the energy sector. However, their intermittent nature necessitates the use of energy storage systems (ESS) to store surplus electricity for times when renewable energy production is insufficient to meet demand [8]. Hydrogen fuel cell-based energy storage systems emerge as a promising solution to address the challenges associated with increased reliance on renewable electricity. During periods of excess generation, surplus electricity can be utilized to produce green hydrogen through water electrolysis, which is then stored as compressed gas in specialized tanks. Subsequently, when there's a deficit in the power supply, stored hydrogen can be converted back into electricity via fuel cells [9].

Opting for hydrogen fuel cell-based energy storage systems proves advantageous owing to several factors. Firstly, these systems boast high energy density, ensuring efficient storage of energy.

Additionally, they incur minimal energy loss during storage and conversion processes, thereby maximizing overall efficiency. Unlike traditional batteries, which suffer from energy leakage ranging from 1% to 5% per hour, hydrogen fuel cells maintain their stored energy effectively. Moreover, hydrogen fuel cell systems offer a prolonged lifespan, making them suitable for long-term use in power systems. In contrast, batteries not only exhibit lower energy density but also tend to degrade more rapidly over time, rendering them less suitable for extended operational durations. Therefore, considering these benefits, hydrogen fuel cell-based systems emerge as a prudent choice for sustainable and reliable energy storage solutions. [10].

Numerous scholarly works have delved into the issue of powering telecommunication base transceiver stations and towers through the integration of renewable energy sources as the primary power supply. Within the academic literature, researchers have extensively explored various methodologies and strategies aimed at harnessing renewable energy to meet the energy demands of these critical infrastructures. These studies have examined the feasibility, effectiveness, and sustainability of employing renewable energy technologies such as solar, wind, and hydroelectric power to power telecommunication facilities. By leveraging renewable energy sources, researchers seek to reduce reliance on conventional fossil fuel-based energy systems, mitigate environmental impacts, and enhance the resilience and efficiency of telecommunication networks. Through comprehensive analyses and case studies, these research endeavors contribute valuable insights and recommendations to the ongoing efforts towards achieving sustainable and eco-friendly energy solutions for telecommunication infrastructure worldwide. R. Kaur et al. conducted a comprehensive assessment of the techno-economic viability of implementing a PV-Wind-based DC microgrid to power a telecom tower. Their study utilized the NSGA II algorithm to determine the optimal size and cost of energy (COE) for the system [11].

In a separate study, the authors conducted an investigation into the technical, economic, and environmental efficacy of diverse hybrid power systems tailored for remote telecommunication stations. Using HOMER Software, they analyzed multiple configurations to identify the most favorable setup based on criteria such as net present cost (NPC) and COE [12].

Jansen et al. presented a case study on powering telecommunication base stations near Dakar, Senegal, utilizing an autonomous renewable energy microgrid. This system employed solar photovoltaic (PV) and wind turbine (WT) technologies for electricity generation, supplemented by a regenerative hydrogen fuel cell for backup power lasting up to 10 days [13].

An analysis to assess the viability and environmental implications of various hybrid systems integrating PV, wind, and DG technologies was conducted in [14]. This investigation aimed to evaluate the potential of these hybrid systems in providing power to telecommunication base transceiver stations situated in rural regions of the Democratic Republic of Congo.

R. K. Pachauri and Y. K. Chauhan proposed a hybrid PV/fuel cell (FC) power system for a telecom base station in India, demonstrating its cost-effectiveness compared to conventional power systems [15].

Zegueur et al. conducted a techno-economic evaluation of a hybrid PV-WT-DG system powering a rural telecommunication station in Algeria's northeast region [16].

In another study , an algorithm was developed to optimize a hydrogen-centric energy storage system, with a focus on minimizing curtailments of renewable energy sources (RES). Implemented in an independent power network in the Aegean Sea, this framework effectively utilized surplus RES energy for grid reinforcement and transportation, achieving up to 39% utilization of otherwise wasted renewable energy output [17].

The primary objective of this research is to transition the conventional diesel generators currently employed in telecommunication stations to a fully renewable energy system. This system will rely entirely on renewable energy sources, with a hydrogen tank serving as the energy storage medium, ensuring uninterrupted power supply through the utilization of fuel cells during periods of power shortage. To conduct a comprehensive analysis, the study employs HOMER Pro (Hybrid Optimization Model for Multiple Energy Resources) software, enabling a thorough techno-economic assessment of the proposed system. Through the utilization of this software, the study aims to determine the optimal sizing for each component of the renewable energy system, ensuring efficiency, reliability, and cost-effectiveness.

This research pioneers the integration of a renewable-hydrogen system specifically designed for telecom stations as a clean and sustainable alternative to traditional diesel generators. By incorporating hydrogen-based energy storage and fuel cell technology, it advances clean energy solutions that align with global efforts to combat climate change and promote sustainable development, reducing the carbon footprint of telecommunication operations. By addressing technical, economic and environmental aspects, this work presents a scalable solution adaptable to similar off-grid and rural applications.

The remainder of this paper is structured as follows: Section 2 presents the materials and methodology utilized in this study. Section 3 discusses the results obtained and provides an analysis of the findings. Finally, Section 4 presents the conclusions drawn from the study's outcomes.

2. MATERIALS AND METHODOLOGY

HOMER®, a robust optimization tool pioneered by the U.S National Renewable Energy Laboratory (NREL), stands as a cornerstone in the realm of renewable energy analysis and planning. It encompasses a comprehensive three-step analytical process, comprising Simulation, Optimization, and Sensitivity Analysis, to facilitate intricate decision-making processes. At its core, HOMER® relies on a multitude of input data parameters, encompassing geographical positioning, load profiles, solar radiation levels, wind speeds, ambient temperatures, as well as economic and technical constraints, among others [18]. These inputs form the foundation upon which the tool constructs and evaluates diverse energy system scenarios, aiding in the identification of optimal solutions tailored to specific environmental and operational contexts. Within the forthcoming sections of this paper, detailed discussions on the requisite input data and the conceptual model underpinning the proposed renewable energy system shall be presented. This delineation serves to provide a comprehensive understanding of the analytical framework employed, laying the groundwork for subsequent analyses and interpretations.

The methodology followed for the study is depicted in Figure 1.

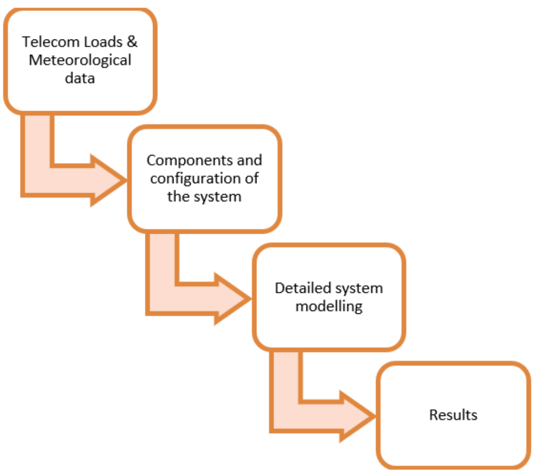


Figure 1. Simulation steps.

2.1. Telecom load and site localization

In this research, the telecom load under investigation pertains to the electrical consumption exhibited by a base transceiver station situated within a remote locale of Collo, located in the Skikda province, northeastern Algeria. The geographic coordinates of the site are recorded as 37°0.8'N latitude and 6°33.8'E longitude.

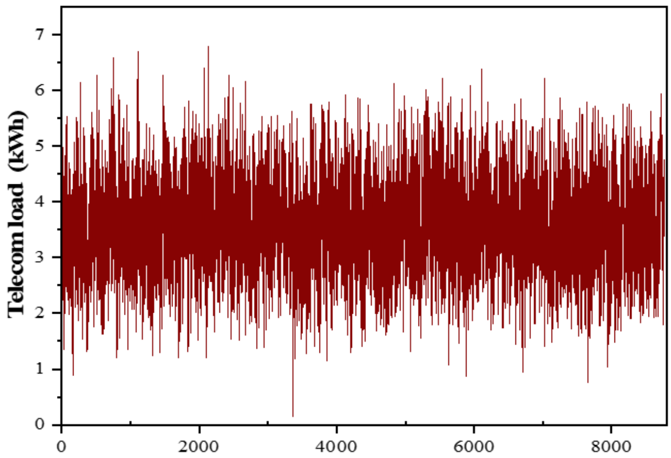


Figure 2. Hourly load profile of the DC telecom load.

The hourly telecom load profile, depicted in Figure 2, delineates the temporal distribution of energy consumption patterns. Characterized as a direct current (DC) load, it showcases an average daily consumption rate of 85 kilowatt-hours (kWh). This data serves as a fundamental basis for assessing the energy requirements and operational dynamics of the telecommunication infrastructure within the specified geographical context.

2.2. Wind and Solar potential of the studied site

The geographical location of the telecommunication station presents a notable potential for harnessing renewable energy. To evaluate the wind and solar resources available, HOMER® software integrates with NASA's surface meteorology and solar energy database to acquire comprehensive weather data specific to the station's coordinates.

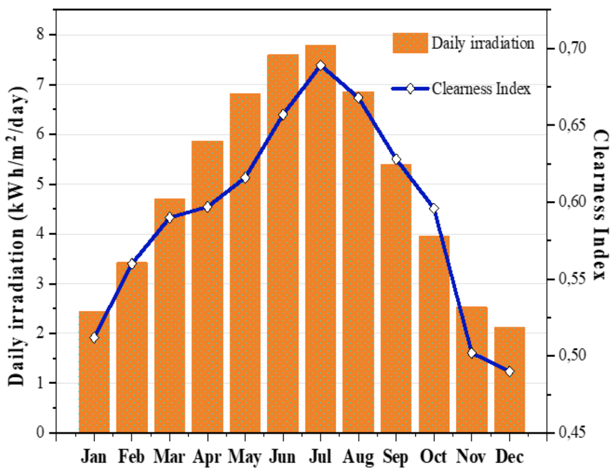


Figure 3. Monthly average solar radiation and clearness index of the site.

Figure 3 illustrates the monthly fluctuations in solar radiation levels, while Figure 4 portrays the variations in wind speed observed at the selected site. According to the analysis, the annual average solar radiation at the site is estimated to be 4.75 kWh/m²/day, with the highest levels recorded in July, peaking at 7.18 kWh/m²/day.

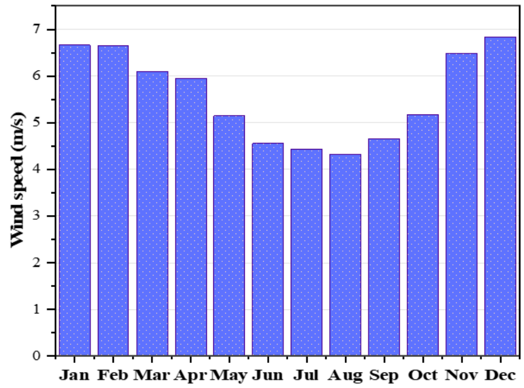


Figure 4. Monthly average wind speed.

This variation indicates a significant seasonal fluctuation in solar energy availability. Similarly, the annual average wind speed is calculated to be 5.58 m/s, with December exhibiting the highest wind speeds, reaching 6.84 m/s. This data suggests seasonal variability in wind energy potential, with December being the most conducive month for wind power generation. The assessment of wind and solar potential highlights the considerable renewable energy resources present at the study site, emphasizing the viability of integrating wind and solar energy technologies into the telecommunication station's power supply system.

2.3. Technical model

The hybrid energy system under investigation, represents a sophisticated PV-Wind configuration integrated with a hydrogen storage infrastructure. This system incorporates essential components such as an electrolyzer, a fuel cell, and a hydrogen tank. During periods of surplus electricity generation, the electrolyzer facilitates the conversion of excess power into hydrogen, which is subsequently stored within the hydrogen tank. This stored hydrogen serves as a reserve energy source, strategically utilized by the fuel cell during instances of inadequate power generation to fulfill the prevailing load demand. This seamless interplay between renewable energy generation, hydrogen production, and subsequent utilization within the system ensures optimal energy management and continuous supply reliability, even under fluctuating environmental conditions or variable energy output scenarios.

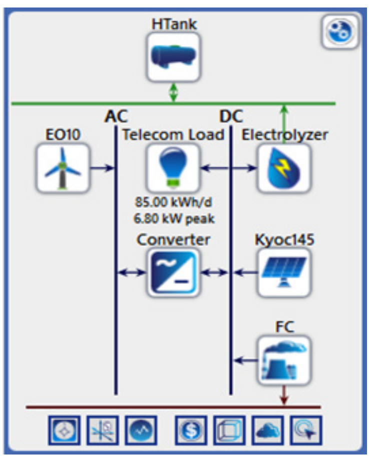


Figure 5. Schematic of the proposed system.

Figure 5 represents the proposed hybrid energy system for the telecom station supply.

3. GOVERNING EQUATIONS

3.1. PV System

PV panels serve as pivotal elements within numerous RES, efficiently transforming incident solar radiation into electrical energy through the photovoltaic effect [19]. The power output of a PV array can be rigorously computed utilizing the following mathematical expression [20]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) \left(1 + \alpha_p \left(T_c - T_{c,STC}\right)\right) \qquad (1)$$

Where the Y_{PV} represents the rated power of the photovoltaic (PV) array, denoted in (kW), f_{PV} signifies the derating factor expressed as (%), G_T and $G_{T,STC}$ respectively stand for the solar radiation incident on the PV array and the standard incident radiation, quantified in (W/m^2). α_p is the power temperature coefficient in (%/C°). T_c and $T_{c,STC}$ represent the PV cell temperature and the standard temperature in (°C), respectively.

In this study, the selected PV panel model is identified as the flat plate Kyocera 145 SX-UFU series. This specific PV panel is characterized by a nominal power rating of 145 W. Additionally, it exhibits a derating factor of 88%, signifying the reduction in power output under non-optimal operating conditions. The temperature coefficient associated with this PV panel is noted to be -0.46, denoting the rate of decline in power output with increasing panel temperature. The operational lifetime expectancy of the PV panel is conservatively estimated to span 25 years, accounting for gradual degradation over time. To optimize the sizing of the PV system, the HOMER optimizer tool was employed, facilitating the determination of the most suitable PV capacity for the intended application.

3.2. Wind Turbine

In the computation of the electrical power generated by the wind turbine, HOMER employs a rigorous three-step process. Initially, it determines the wind velocity measured at the hub height of the WT utilizing the well-established power law equation [21]:

$$U_{hub} = U_{anem} \left(\frac{z_{hub}}{z_{anem}} \right)^{\alpha} \qquad (2)$$

Where, U_{hub} is the wind speed at the hub height (m/s), U_{anem} represents the velocity measured at the height of the anemometer (m/s). Z_{hub} and Z_{anem} the respective heights (measured in meters) of the hub and the anemometer in (m). α is the power law exponent.

This equation relates the wind speed at the turbine hub to the wind speed at a reference height, typically measured at meteorological masts.

Following the determination of the wind speed U_{hub} by the HOMER software, it references the characteristic power curve of the WT to estimate the anticipated power output at that specific wind speed, assuming standard conditions of temperature and pressure. Subsequently, to accommodate real-world conditions, the predicted power output undergoes adjustment by multiplying it with the air density ratio, as illustrated by the equation below [16]:

$$P_{WT} = \left(\frac{\rho}{\rho_0} \right) P_{WT,STP} \qquad (3)$$

Where ρ is the actual air density in (kg/m^3), ρ_0 is the air density under standard conditions in (kg/m^3). P_{WT} and $P_{WT,STP}$ denote the respective output power of the wind turbine under real-world conditions, and the wind turbine output power adjusted to standard temperature and pressure, both measured in (kW).

In this study, the selection process involved choosing an Eocycle wind turbine characterized by a rated power output of 10 kW. It is pertinent to note that this turbine boasts a projected operational lifespan spanning 20 years, indicating its durability and long-term viability. Additionally, the hub height of this turbine stands at 16 meters, a dimension crucial for optimizing wind capture efficiency.

To determine the most effective configuration, the HOMER optimizer, renowned for its capacity to conduct intricate analyses and optimization processes in energy systems, was employed. Leveraging the capabilities of this software, the study aimed to identify the optimal number of wind turbines required to meet the specified energy demands efficiently. Through meticulous simulation and modeling techniques facilitated by the HOMER optimizer, the study sought to ascertain the most cost-effective and energy-efficient solution for the integration of wind power within the telecommunication infrastructure.

The Kyocera PV panels and Eocycle turbines were selected for their high efficiency and durability and their availability in the local market, ensuring alignment with site-specific climatic and operational requirements.

3.3. Electrolyzer

Water electrolysis is a fundamental electrochemical process involving the splitting of water molecules into hydrogen and oxygen gases. This process occurs within an electrolyzer cell comprising two electrodes: a cathode and an anode. At the cathode, hydrogen gas (H_2) is generated through the reduction reaction, while at the anode, oxygen gas (O_2) is produced via the oxidation reaction. These reactions can be represented as follows [22]:

$$2H^{+}+2e^{-}\rightarrow H_{2} \qquad (4)$$

$$H_{2}O\rightarrow \frac{1}{2}O_{2}+2H^{+}+2e^{-} \qquad (5)$$

This electrochemical process is governed by various factors including the electrolyte composition, electrode materials, applied voltage, and temperature. Understanding the intricacies of water electrolysis is crucial for the development and optimization of efficient and sustainable hydrogen production technologies, with significant implications for renewable energy storage and utilization.

The process of electrolysis of water stands as a firmly established technological method for hydrogen generation, particularly leveraging renewable electricity sources, owing to its notable energy efficiency [23]. Alkaline and Proton Exchange Membrane (PEM) electrolyzers stand out as the predominant and readily accessible variants in the electrolysis landscape [24]. The power consumption of an electrolyzer can be mathematically represented as follows [25]:

$$P_{EL}=\frac{\dot{m}_{H_{2}}HHV_{H_{2}}}{\eta_{EL}} \qquad (6)$$

Where η_{EL} is the efficiency of the electrolyzer, HHV_{H2} is the higher heating value of hydrogen (MJ/kg) and $\dot{m}_{H_2}$ is the hydrogen flow rate at the electrolyzer output (kg/s).

In this study, a generic electrolyzer characterized by an operational efficiency of 85% and a projected operational lifespan spanning 15 years was employed. The search space for the parameter exploration was meticulously defined, encompassing potential electrolyzer capacities of 10 kW, 20 kW, and 50 kW. These specific capacity ranges were selected to encompass a diverse array of potential operational scales, thereby facilitating a comprehensive assessment of the electrolyzer's performance across varying power outputs. This deliberate approach to parameter selection and experimentation design ensures robustness and reliability in the study's findings, enabling meaningful insights into the efficiency and viability of electrolysis technologies for hydrogen production applications.

3.4. Fuel cell

Fuel cells operate via a complementary electrochemical process to electrolysis. Functioning as electrochemical cells, fuel cells consist of both an anode and a cathode, mirroring the configuration of electrolyzers. At the anode, hydrogen molecules undergo oxidation, releasing protons and electrons according to the following reaction [26]:

$$2H_2 + 4e^- \rightarrow 4H^+ \qquad (7)$$

Simultaneously, at the cathode, oxygen molecules are reduced, combining with the protons and electrons from the anode to form water [26]:

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \qquad (8)$$

The voltage produced by these reactions determines the electrical output of the fuel cell. This voltage can be expressed mathematically as elucidated by [27], [28]:

$$V_{FC} = E_{rev} - V_{act} - V_{diff} - V_{\Omega} \qquad (9)$$

Where E_{rev} is the reversible voltage, V_{act} is the activation voltage, V_{diff} is the diffusion voltage and V_{Ω} is the ohmic voltage.

These fundamental electrochemical processes underscore the functionality of fuel cells as efficient and environmentally friendly energy conversion devices, with applications ranging from transportation and stationary power generation to portable electronics and backup power systems.

In the present study, a standardized fuel cell characterized by a nominal operational lifespan of 50,000 hours was employed as the primary research apparatus. The parameter space under scrutiny was delineated to span from 5 kW to 20 kW, with incremental steps of 5 kW meticulously stipulated. This systematic exploration of the specified power range allows for comprehensive analysis and comparison of performance metrics across various power output levels.

3.5. Hydrogen tank

In the devised system, a hydrogen storage tank plays a critical role in efficiently managing the surplus hydrogen generated by the electrolyzer during periods of heightened power production from photovoltaic (PV) and wind sources. This surplus hydrogen is effectively stored within the tank, poised to be utilized during instances of insufficient power generation to meet the requisite load demand. A key assumption underpinning this storage mechanism is the absence of any hydrogen leakage from the tank, ensuring the integrity and longevity of the stored hydrogen supply. Furthermore, to initialize the storage capacity, an initial quantity of hydrogen equivalent to 10% of the tank's total volume is established. The exploration of optimal storage capacities is conducted within a predetermined search space, spanning volumes of 50 kg, 100 kg, and 150 kg, facilitating a comprehensive analysis of storage requirements to accommodate varying levels of hydrogen production and demand dynamics.

3.6. Power converter

In the telecommunications system under consideration, the load primarily comprises direct current (DC), whereas the power output from the wind turbine manifests as alternating current (AC). Consequently, to synchronize these disparate electrical outputs, a rectifier is incorporated

into the system. Operating with a commendable efficiency rating of 95% and boasting a substantial lifespan of 15 years, this rectifier facilitates the conversion of AC to DC, ensuring compatibility with the telecom load requirements. The determination of the optimal capacity for this converter is achieved through the utilization of the HOMER optimizer, leveraging its advanced algorithmic capabilities to ascertain the most efficient configuration.
A comprehensive depiction of the entire system configuration is provided in Figure 4, offering a visual representation of the interconnections and component placement within the system architecture. Additionally, pertinent economic data on each component are meticulously detailed in Table A.1 in the appendix, providing essential insights into the financial considerations associated with the project implementation.

3.7. Economic model

Homer PRO's main objective function is minimizing the total net present cost (NPC) also known as the life cycle cost (LCC) by which the software ranks all the technically feasible configurations of the optimization results. A system's NPC is the present value of all incurring costs throughout its lifespan minus the present value of all earned revenues. It can be expressed as follows [21]:

$$C_{NPC,tot} = \frac{C_{ann,tot}}{CRF} \qquad (10)$$

Where $C_{ann,tot}$ is the total annualized cost ($/year) and CRF is the capital recovery factor expressed as:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \qquad (11)$$

N is the number of years and i is the annual real discount rate (%).
Another substantial metric for evaluating a system's economic performance is the levelized cost of energy (LCOE) which is the cost of producing 1kWh of useful energy. It can be calculated as follows [21]:

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \qquad (12)$$

Where $C_{ann,tot}$ is the total annualized cost ($/year) and E_{served} is the total electrical load served (kWh/year).
For systems with hydrogen production, the levelized cost of hydrogen (LCOH) is another key parameter that designates the average cost of one kilogramme of produced hydrogen. For off-grid systems, the LCOH can be expressed as [29]:

$$LCOH = \frac{C_{ann,tot}}{\dot{L}_{H_2}} \qquad (13)$$

Where $\dot{L}_{H_2}$ represents the total annual hydrogen load, summed over 8760 hours (one full year). It is imperative to note that the envisioned project operates under a projected lifetime of 25 years, reflecting the long-term sustainability and viability of the proposed infrastructure. Moreover, the simulation process is conducted with a time step interval of 1 hour, facilitating precise and granular analysis of system performance and operational dynamics over the project's lifespan. The real discount rate is taken as 5.88%.

4. RESULTS AND DISCUSSION

This section presents the outcome results of the HOMER simulation. HOMER calculates all possible scenarios based on the economic input data, the technical constraints, the resource availability, and the load profile to find the optimal size that makes the system reliable and cost-effective.

Table 1. Optimal sizing of the proposed system.

Component	**Search space**	**Optimal size (kW)**
PV	HOMER Optimizer™	12.3
Wind turbine	HOMER Optimizer™	2 units
Electrolyzer	10 – 20 – 50 kW	20
Fuel cell	5 – 10 – 15 – 20 kW	10
Hydrogen tank	50 – 100 – 200 kg	50
Converter	HOMER Optimizer™	17.3

Table 2. Techno-economic results of the system's components.

	Scenario	**Base case**	**Hydrogen storage case**
Economic	NPC ($)	123,247	155,705
	LCOE ($)	0.307	0.388
	LCOH ($)	-	10.7
	Initial capital ($)	6830	116,964
	Operating cost ($)	9007	2997
Technical	Electricity production (kWh/year)	32,901	140,600
	Excess electricity (kWh/year)	247	54,268
	Capacity shortage (kWh/year)	30	30.9
	Unmet load (kWh/year)	3.95	18.2
	Total fuel	11,873 L/yr	1074 kg/yr

The results, summarized in Table 1, illustrate the ideal configuration of the proposed system, while further techno-economic insights are elucidated in Table 2.

Table 1 showcases the optimal sizing of key components within the studied system, revealing pertinent details such as the search space considered and the ultimately determined optimal size. Notably, the PV panels are optimized to a capacity of 12.3 kW, while the wind turbines, electrolyzer, fuel cell, hydrogen tank, and converter are tailored to their respective optimal sizes through the HOMER Optimizer™.

Table 2 provides a comprehensive overview of the proposed system's techno-economic metrics compared to the conventional one. The NPC of the project is estimated at 155,705$, accompanied by a levelized cost of energy (LCOE) of 0.388$. This NPC is 14% higher than the base case due to the high initial capital investment costs estimated at 116,964$. However, the annual operating costs were reduced by almost 67%.

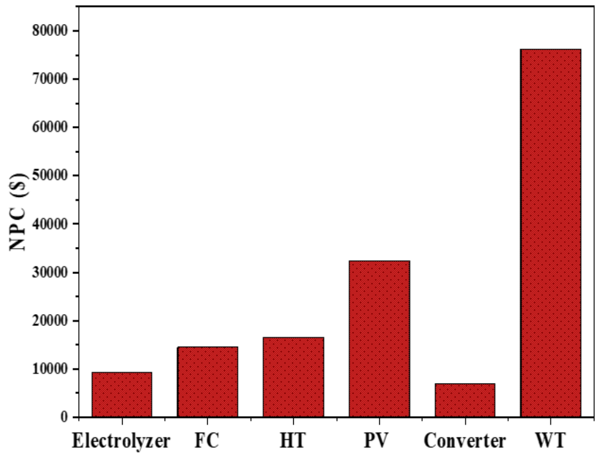


Figure 6. Net Present Cost per component.

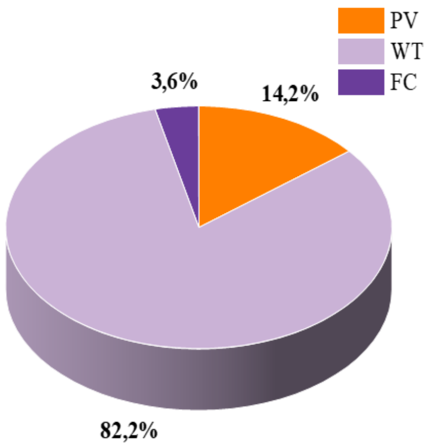
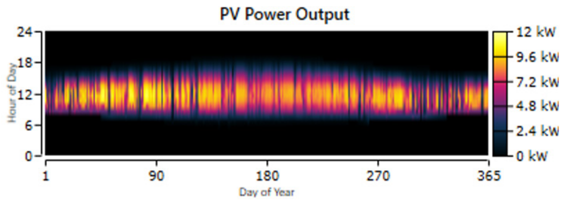
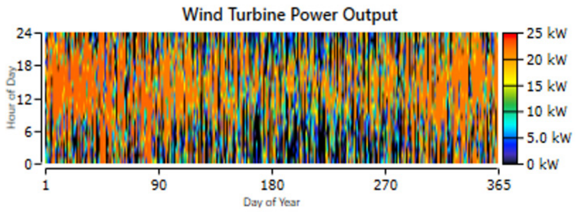


Figure 7. Annual electric production shares.

Figure 6 illustrates that the NPC per component within the system configuration varies significantly, reflecting diverse investment requirements and operational considerations. Specifically, the electrolyzer presents a relatively lower NPC at $9290.39, followed by the system converter at $6980.94. Conversely, the wind turbine exhibits the highest NPC among the components, standing at $76,104.8. In between, the fuel cell, hydrogen tank, and PV panels demonstrate intermediate NPC values at $14,502.48, $16,463.76, and $32,362.32, respectively. From a technical standpoint, the system demonstrates robust performance, generating an annual electricity output of 140,600 kWh/year. This production is derived primarily from PV panels contributing 19,967 kWh/year, wind turbines generating 115,521 kWh/year, and fuel cells providing 5,112 kWh/year, accounting for 14.2%, 82.2%, and 3.6% of the total output respectively, as depicted in Figure 7. The total electricity produced is devided as follows: 22.05% for the telecom load consumption, 37.08% for electrolysis, 38.59% of excessive energy and 2.26% converter losses. It is important to note the presence of other potential energy losses across the system that can significantly affect the overall efficiency. These losses mainly stem from conversion losses particularly in the electrolyzer and the fuell cell where there is a transformation between different energy froms. Another type of losses is the transmission losses, which are primaly associated with the movement of electricity among components due to electrical resistance in wires, connectors and other transmission mediums. Ultimately, there are storage-related losses although hydrogen storage is known for low energy loss and minimal leakage over long duration compared to battery storage, some minor energy consumption occurs for tasks such as compression. These losses combined reduce the hybrid system's effective output.



(a)



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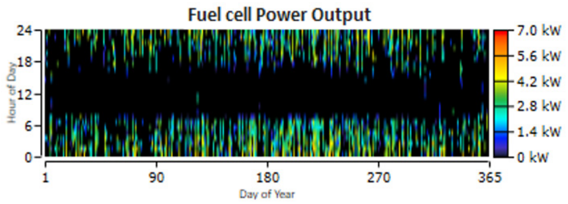

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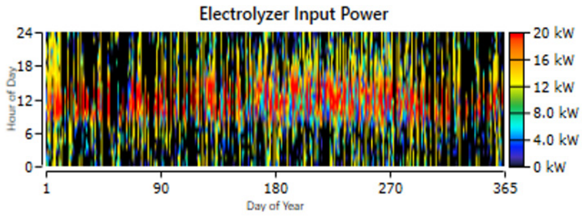

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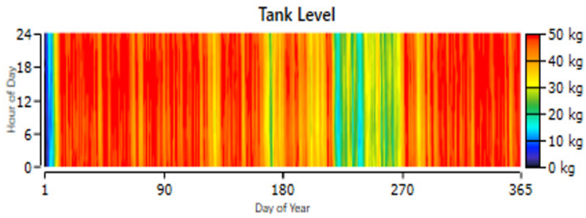

(e)

Figure 8. Daily power output, electrolyzer input, and hydrogen tank level.

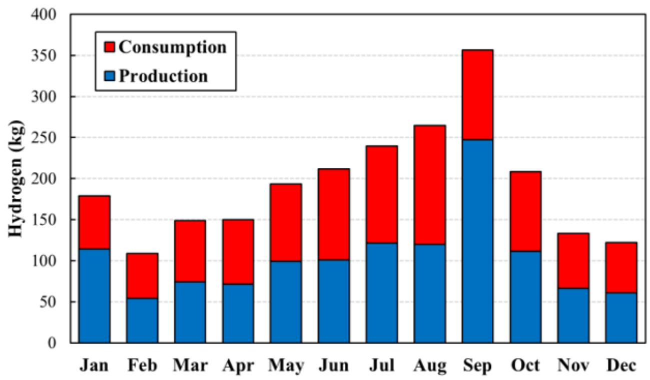

Figure 9. Monthly hydrogen fuel production and consumption.

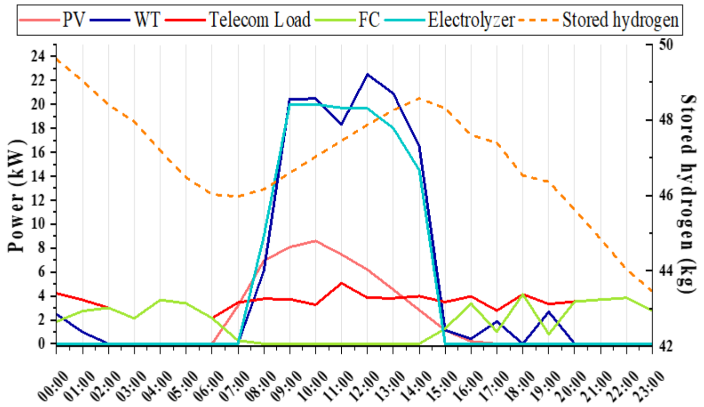

Figure 10. Hourly energy management of the system.

The analysis presented in this section offers a detailed insight into the daily power outputs of key components within the green power system, shedding light on their operational dynamics and efficiency. Figure 8 illustrates the daily power outputs of the PV panels, wind turbines, and fuel cells, alongside the daily input power of the electrolyzer and the fluctuation of hydrogen tank levels. The PV array demonstrates consistent performance, generating a daily mean output of 54.7 kWh/day over 4086 operational hours per year, with a corresponding levelized cost of 0.125$/kWh. Similarly, the wind turbines operate for 7034 hours annually, yielding the highest electricity production contribution with a mean output of 13.2 kW/day and a favorable levelized cost of 0.051$/kWh. Meanwhile, the fuel cell, serving as the backup power system, operates for 3150 hours yearly, consuming 1074 kg of hydrogen fuel with a specific fuel consumption of 0.210 kg/kWh. The electrolyzer plays a pivotal role in the system's energy management, with a mean input of 5.95 kW/day and an operational duration of 4669 hours annually. It produces 1124 kg/year of hydrogen, contributing to the hydrogen tank's storage capacity. Throughout the year, the hydrogen tank maintains a dynamic level, starting with zero kg of content and concluding with 50 kg, after accounting for hydrogen production and consumption. Figure 9 displays the monthly hydrogen fuel production and consumption. The system's annual hydrogen production rate is estimated at 1124 kg and the consumption rate is estimated at 1074 kg, providing a reliable backup power source when renewable generation is insufficient. Figure 10 provides a comprehensive overview of the hourly energy management for a representative day, showcasing the system's dispatch strategy, which utilizes a load-following approach. This strategy is particularly suitable for systems characterized by high renewable energy penetration, ensuring optimal utilization of available resources.

The hydrogen energy system serves as a crucial backup power source, activating during periods of renewable energy deficiency or power shortages to meet load demand. Conversely, the electrolyzer operates during periods of excess renewable energy production, converting surplus electricity into hydrogen for storage. Notably, if the hydrogen tank reaches full capacity, excess energy cannot be stored, highlighting a potential area for optimization. However, Implementing green hydrogen energy systems presents several challenges. Infrastructure requirements, such as the need for specialized storage tanks and pipelines, demand significant investment and development due to the current lack of extensive hydrogen networks. Safety considerations are crucial as hydrogen is highly flammable, requiring careful handling to prevent leaks, explosions, or material degradation. Additionally, while hydrogen technologies like electrolyzers and fuel cells are progressing, they are not yet fully mature or cost-competitive with other energy storage solutions, limiting their widespread adoption. Overcoming these challenges will require ongoing technological advancements and infrastructure development.

Table 3. Environmental comparison between the base case and the proposed system.

Pollutants (kg/year)	Base case	Hydrogen storage case
Carbon Dioxide	31,081	-0.337
Carbon Monoxide	194	0.215
Unburned Hydrocarbons	8.55	0
Particulate Matter	1.16	0
Sulfur Dioxide	76.1	0
Nitrogen Oxides	182	0.0215

Table 3 provides a comparative analysis of pollutant emissions between the traditional power system and the proposed hydrogen storage system highlighting the environmental advantages of the proposed system over the conventional one. Notably, the significant reduction in greenhouse gas emissions, particularly CO_2 where the proposed system could avoid emitting nearly 31,081 kg of CO_2 annually.

A comparative analysis was conducted between the proposed PV–wind–hydrogen system and a previously studied PV–wind–diesel–battery hybrid system [16]. The latter achieved an NPC of $85,673 and COE of $0.214/kWh, with CO_2 emissions reduced by approximately 57% compared to a diesel-only baseline. However, its reliance on diesel generation results in ongoing fuel costs and emissions. By contrast, the hydrogen storage system, while involving a higher initial NPC of $155,705, operates with zero emissions and does not require diesel, providing a fully sustainable alternative. This configuration is particularly suited for locations with high renewable potential, where hydrogen can be efficiently stored and used as backup, ensuring system reliability for off-grid telecommunication loads.

From an Environmental Science and Pollution Research perspective, these findings underscore the importance of efficient energy management strategies in maximizing the utilization of renewable resources while minimizing environmental impact. Moreover, the analysis suggests potential avenues for further research, such as exploring alternative methods for utilizing excess energy or optimizing storage capacity to enhance system flexibility and resilience. Overall, the results contribute to advancing the understanding of sustainable energy systems and their implications for environmental sustainability.

5. SENSITIVITY ANALYSIS

In this section, a sensitivity analysis is conducted to assess the impact of the meteorological data variations on the system's main economic metrics: NPC, LCOE and LCOH. The solar irradiation and wind speed average values were changed by ±20%.

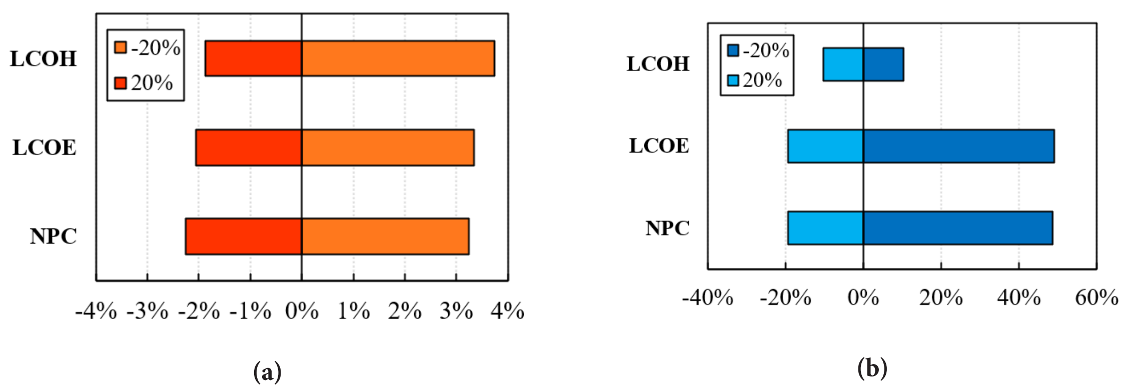

Figure 11. Sensitivity analysis results of: (a) Solar irradiation; (b) wind speed.

The sensitivity analysis results, presented in Figure 11, reveal an inverse relationship between meteorological inputs and economic outputs. A 20% increase in solar irradiation leads to a modest decrease in NPC, LCOE, and LCOH (approximately 1–2%), while a 20% decrease results in up to a 3% increase in these economic metrics. These findings underscore the resilience and cost-effectiveness of the PV system, even under fluctuating solar conditions. In contrast, wind speed variations demonstrate a significant impact on economic outcomes, with a 20% reduction in wind speed causing an almost 50% increase in NPC and LCOE.

6. CONCLUSION AND FUTURE WORK

The simulation outcomes convincingly demonstrated the techno-economic viability of the system, revealing a total NPC of $155,705 and a COE amounting to $0.388. Notably, the optimal configuration featured a 12.3 kW PV power capacity, complemented by two 10 kW wind turbines, a 10-kW fuel cell, a 20 kW electrolyzer, a 50 kg hydrogen tank, and a 17.3 kW rectifier. With an annual electricity production of 140,600 kWh/year, wind energy emerged as the predominant contributor, underscoring the system's robustness and reliability.

Furthermore, our analysis identified a negligible annual capacity shortage of 0.0372% and an unmet load of merely 0.0219%, affirming the system's capability to meet the telecom load demand effectively. Notably, the hydrogen tank demonstrated commendable performance, successfully storing 1174 kg of on-site produced hydrogen over the course of the year.

The sensitivity analysis results demonstrated the resilience of the PV power system, in contrast to the wind system which showed significant economic instability under variable conditions. These findings emphasis the critical importance of accurate meteorological data in optimizing system design for economic stability.

Limitations of the study include dependency on simulation outputs, location-specific results, and assumptions on component durability and financial factors, which may affect generalizability.

Beyond its economic prowess, the proposed system stands out for its environmental integrity, boasting a 100% green profile with zero pollutant emissions. This aspect holds significant promise in mitigating global warming and advancing sustainable energy practices. We anticipate that our findings will serve as a catalyst, inspiring telecom companies to embrace green power solutions for their towers and stations, thereby fostering a more environmentally conscious telecommunications sector.

Our future work will focus on detailed analysis of hydrogen consumption and system efficiency under varying conditions, exploration of advanced optimization techniques for component selection and sizing, and investigations into the infrastructure and integration challenges of hydrogen storage systems. Additionally, we propose developing enhanced safety protocols specific to hydrogen handling, conducting cost and technological maturity assessments, and implementing pilot projects to evaluate real-world feasibility. We believe these directions will provide a comprehensive foundation for future advancements in green hydrogen energy storage.

Authors contribution: AZ: conceptualization, methodology, data curation, writing—original draft, formal analysis, visualization, supervision, writing—review and editing. ST: investigation, conceptualization, methodology, supervision, writing—original draft, writing—review and editing. AM: conceptualization, data curation, supervision.

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APPENDIX

Component	**Capital ($/kW)**	**Replacement ($/kW)**	**O&M ($/year)**
Kyocera 145 W	2500	2500	10
Eocycle 10 kW	3000	3000	300
Converter	300	300	0
Electrolyzer [30]	300	290	5
Fuel cell [30]	500	450	0.02 ($/op.hr)
Hydrogen Storage [31]	200 ($/kg)	150 ($/kg)	10