Techno-economic Analysis of Hybrid Renewable Energy System for Hydrogen Production in the Demnate Region of Morocco

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Abstract: - This paper investigates the techno-economic feasibility of producing electrical energy for three villages in the mountains in the Demnate region. The community needs were determined based on the site visit to identify the electrical load demand in reality. In addition, a site description was done to evaluate the suitable system to produce the electrical energy. Using the Homer software, two systems were selected to produce electricity and hydrogen which are described as follows: The first system is constituted of a PV-Generator with 3759 kW, an Autosize Genset generating 300 kW, a DC/ AC converter supplying 317 kw, 800 kW produced by the electrolyzer, and a hydrogen storage tank with 900 Kg as a capacity. The second system is composed of PV modules with 3743 kw, seven G3 wind turbines with 3kW, an Autosize Genset generating 300 kw, 323 kW of power converters, a generic electrolyzer with an output power of 800 kW, and a hydrogen tank with 900 Kg as capacity. In addition, the financial analysis gives 1.56$/kWh and 1.57$/kWh as the Levelized Cost of Energy and 15.6 M$ and 15.7 M$ as the Net Present Cost for the first and second systems respectively.

Key-Words: - Hydrogen, techno-economic study, renewable energy systems, energy storage, Morocco, hydrogen storage, Pv system,, Turbine Wind system, LCOE, NPC.

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1 Introduction

Faced with the intermittency of renewable energy systems (RES), energy storage systems (ESS) are defined as one of the promising solutions to ensure the balance between the rural and urban population's needs and renewable energy intermittent production. Indeed, several types of ESS have been introduced in many literatures to solve the previously mentioned problem including pumped hydro storage (PHS), compressed air energy storage (CAES), thermal energy storage (TES), electrostatic and magnetic energy storage (EMES), and electrochemical energy storage (ELMES), [1]. Furthermore, numerous studies have been conducted to investigate the feasibility of using RES with the ESS option to promote electrical energy access to cities and rural areas, [2], [3], [4]. The adoption of ESS to produce electrical energy is highly recommended by researchers due to the high cost of grid extension especially for rural and isolated areas.

The ESS are used in multiple types of service including schools, universities, and hospitals, [5], [6], [7]. For the reason that the well-managed use of ESS can highly improve several populations' lives by providing electrical energy to health and education buildings. For instance, in the Siyambalanduwa region of SIRILANKA, an off-grid hybrid energy system was designed to electrify rural areas due to the national grid's non-existence by using the "HOMER" software tool. Hence, the selected hybrid system to feed the site with electricity was composed of PV, wind, and battery generators with 0.36 $/kWh as a levelized cost of energy, [8]. Similarly, a case study was conducted in a village west of China to investigate the techno-economic feasibility of an off-grid hybrid renewable energy system using the software tool mentioned. The optimization results confirm the effectiveness of the selected hybrid system implementation with 104 kW PV modules, three Wind turbines of 10 kW, 50 kW Biogas fueled Diesel Generator BDG, 331 kWh storage batteries, and 99 kW power converter, which leads to total independence from the grid network in this Chinese village, [4].

Off-grid systems have also emerged for mobile homes as an alternative to grid extension in some countries, such a case study assessed in IRAN to feed mobile homes with electricity using the "TRNSYS" software tool, giving an LCOE of 0.23 $/kWh. The system lacks 2.45%, equivalent to 118 h of required electrical energy, and produces 56% of surplus energy, [9].

On the other hand, ESS is also used to limit stability problems in the network when the PV system is connected to the grid. In particular, grid-connected to residential PV systems with battery supercapacitors were designed and modeled to analyze small signals of the proposed system. As a result, the ESS has the advantage of providing a dynamic performance and a rapid response during the load and PV generation changes, [10]. However, some disadvantages occur when batteries are used in the long term. Therefore, using batteries as an energy storage component requires three to four times its replacement in case of bad management and the health and environmental harmfulness caused by their usage during the expiration period, [11].

For this reason, and to avoid these inconveniences, several research studies have been carried out on alternatives to replace batteries. It has been found that hydrogen could be an alternative solution to different storage systems.

Recently, the interest in green hydrogen production has been widely increasing. It is considered a promising key for industrial, transportation, and residential sectors by the prediction of its ability to replace fossil fuels. However, the approach that aims to adopt hydrogen practically in different sectors, is still lacking resources and studies to come up with a global view concerning the future of green hydrogen production and its use.

To respond to these scientific and industrial needs, different strategies were proposed by researchers to enhance effective hydrogen production. It is classified based on two levels: the first one depends on the importance of energy sources such as electrical, biochemical, thermal, and material used in the production process including fossil fuels, water, biomass, and water, while the second depends on the component used during the production process (electrolyzer …etc.), [12].

Indeed, the hydrogen production method's performance depends on several criteria that mainly involve technical, economic, thermodynamic, environmental, and social criteria. Based on these aspects, a performance comparison of different production methods has been conducted in the literature, [13]. In conclusion, high-temperature electrolysis provides the highest energy efficiency while photo fermentation has the lowest energy efficiency and CO2 emissions. Therefore, the hybrid thermochemical cycle is the most efficient among the others in terms of energy efficiency.

Among the various hydrogen production methods, the one based on renewable energy sources is the most concerned in the energy transition phase. Despite its implementing advantages, it is still insufficient to get a clear road map in different fields and sectors. Especially in the African continent is especially known for its huge diversity and potential for renewable energy sources, which might make it the main green hydrogen producer and exporter to the rest of the world.

So, the right use of this diversity of renewable resources can guarantee self-satisfaction for countries that are most dependent on fuels in the industry sectors. As a result, conducting studies about the feasibility of hydrogen production and integrating its technology in African countries is recommended. Several researchers have studied the necessary criteria to produce green hydrogen purely based on RES. In [14], The study claims that Africa could export 20.90 % of the hydrogen to the European market due to the potential of available RE resources 34.88% and the high number of population's youth (13.95 %) while the ammonia production according to the research goes to 20.90%.

Other encouraging studies propose the use of green hydrogen in the transport sector as a replacement for fossil fuels by profiting from its nontoxicity, [15]. The study aims to assess a techno-economic investigation of a wind-hydrogen refueling station in seven South African cities. The station was designed to feed 25 green hydrogen vehicles daily with 5 tanks for each vehicle. Results prove the viability of the station with a competitive price of 6.34 $/kg green hydrogen compared to 8.97 $/kg of fuel price in addition to the CO reduction by 0.133 tons and CO2 emissions by 73.95 tons per year. Similarly, in Niger, a case study shows the possibility of using hydrogen to provide electricity for the transport sector. The total hydrogen production needed to replace 1% of gasoline and diesel demand toward 2040 is about 0.0117 Mt, while the space required to implement the installation is 5% of the Niger land, [16].

In other regions of the world, like Ningbo in east China, a combined hydrogen and heating system based on solar energy was proposed to constitute an off-grid system that produces 6179 kWh for summer and 3667 kWh for winter seasons, [17].

Correspondingly, in Belgium, a case study was conducted to assess the techno-economic feasibility of using current and future ESS based only on hydrogen including unique battery systems and hybrid storage systems (battery and hydrogen). The first option was not considered a competitive solution compared to the other proposed storage systems, [18].

In one Moroccan city, as illustrated in the literature [19], a refueling station was designed to produce 152 kg/day of green hydrogen to supply the total of electrical taxis with a cost of 9.18 $/kg, while 30. kg/day with 12.56 $/kg is required to feed only 20% of taxis with a cost of 12.56 $/ kg. This research study responds to the Moroccan government's strategy regarding green hydrogen production and renewable energy systems adoption instead of fossil fuels. Therefore, the aim is to enhance the use of renewable energy systems by 52 % by 2030 [20].

Indeed, the focus on rural areas is highly recommended when speaking about electrification availability due to the need to develop these villages, especially since the off-grid system's implementation could be more economical, unlike the grid extension due to the high distance its realization becomes more costly. For this reason, our research work in this paper investigates at the first stage the financial feasibility of integrating the off-grid systems technology with hydrogen storage for 140 families in the Demnate region of Morocco. In the second stage, the off-gird system is compared to the grid extension option to identify the most suitable solution from which the considered region can benefit economically. Finally, a green hydrogen load was considered during the modeling and simulation phase to measure the correspondence between hydrogen storage and its effective consumption. This paper's results were found using the Homer software tools simulation. However, an on-site visit is crucial to identify the software's inputs and the system's power source availability and coherence with the mountains of the Demnate region. The following sections describe the methodology followed in this paper.

2 Hydrogen Project Feasibility and Natural Constraints Conditions

Most commonly reviewed studies propose the exploitation of hydrogen in cities for refulling stations or other sectors. However, the space and cost are still presenting limitations to promote hydrogen-optimized production. As for the cost factor, it can be reduced by developing the production processes and by increasing the common interest in industrial sectors to produce efficient system components with lower costs. For instance, the PV panels and batteries prices were extremely high at the first stage of their production era. However, prices have steadily decreased due to the large competition and technology development, especially after several companies have moved to larger and cheaper land areas. Indeed, off-grid systems with hydrogen storage for rural areas could provide a great solution for different problems including electrical energy access, economic and demographic growth, and self-dependency.

The Moroccan economy is still primarily based on the agri-food sector, especially in rural areas. Therefore, this paperwork aims to investigate the feasibility of integrating off-grid systems in these regions worth considering. In the second stage, the selection of suitable systems configuration to feed their load demands using Homer software tools. The paper proposes also the possibility of benefiting from this promising project in transferring electrical energy to major cities.

3 Methodology of the Project Study

Practically, three villages in the Demnate region of Morocco were selected to investigate the techno-economic feasibility of integrating off-grid systems with green hydrogen storage. Initially, the region's metrological conditions and climate variations were analyzed to choose renewable energy sources highlighting the systems' required components. The second phase is the modeling of the system's components which involves renewable energy sources such as PV modules, wind turbines, and biomass then simulating the whole system to get a response each time of the year. The third is optimizing the system by using the Homer software which is done based on different key factors including the system's cost and annual production LCOE and CNPC.

Figure 1 shows the system components. It comprises PV modules, wind turbines, biomass, DC/DC and DC/ AC power converters, and storage devices.

3.1 The Required Input Data

Input data will be set at the beginning of the project design and simulation via the mentioned software tool. They are required to ensure an appropriate and suitable sizing of the system. The most important inputs are the load demand and meteorological data. In fact, by referring to the selected area's load demand, the system's output (electricity) can be predicted so the system design can fit the village's electrical requirement. In addition, meteorological data are important to assess a correct analysis of the village's renewable energy sources. They provide specific information concerning the weather change and variation yearly, monthly, and seasonally also which leads to selecting the appropriate type of renewable energy source to power the system. Basically, the required meteorological data are solar irradiation, wind speed, humidity, and rain falling which are obtained from the Surface Meteorology and Solar Energy database of NASA (National Aeronautics and Space Administration) as illustrated in Figure 2.

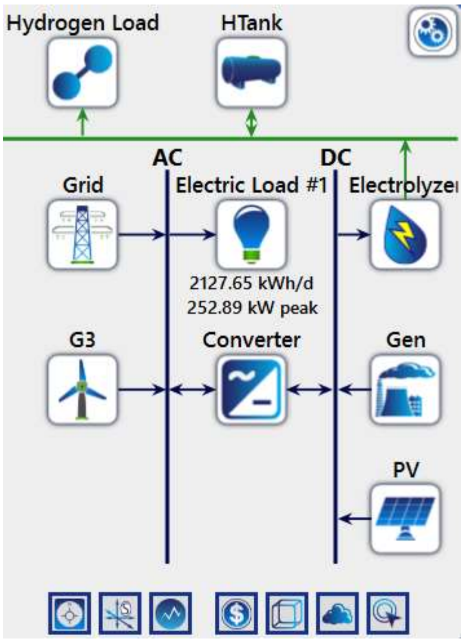


Fig 1: model of the hybrid off-grid system for hydrogen production

3.2 The System Sizing and Simulation Tool Function

The system's size and development are carried out by using HOMER PRO Software. This software is also used to study the performance of the system regarding two main factors which are: the NPC and the LCOE expressed in equations (1), and (2). The software takes into consideration the available renewable energy sources of the mentioned areas, the load demand, the budget of the project, and the space required for the system installation. In addition, the HOMER PRO Software tool allows the detection of all possible options for the system implementation so that the user can easily compare the defined cases in terms of cost and performance.

3.3 Determination of Techno-Economic Indicators and Analysis

The determination of the two main indicators NPC and LCOE of energy cost are taken into account in the techno-economic analysis to define which system is more performant and economical. So, the LCOE represents the cost of useful electrical energy produced by the system per kWh, [21]. It is also considered the major factor in determining the project feasibility and competitiveness and is defined as the division of the annualized cost of the useful produced electrical energy which is calculated by the following equation (1), [22].

$$LCOE = \frac{C_{ann,tot}}{E_{pri}+E_{def}+E_{grid,sales}} \tag{1}$$

Where:
LCOE: is the levellized cost of energy ;
$C_{ann,\ tot}$: is the system's annualized total cost expressed in dollars per year;
E_{pri}: is the primary load served (AC and DC) in kWh/ year;
E_{def}: is the deferrable load served in kWh/ year;
$E_{grid,\ sales}$: is the entire gird sales in kWh/ year.

The NPC indicator is calculated by the following equation (2):

$$C_{NPC} = \frac{C_{ann,tot}}{CRF\ (i,R_{proj})} \tag{2}$$

Where :
C_{NPC}: is defined as the total Net Present Cost in $;
C_{RF}: is defined as the capital recovery factor, i is expressed in %;
R_{proj}: is the lifetime of the project in years;
$C_{ann,\ tot}$: is the system's annualized total cost expressed in $ per year.

3.4 The Impact of Natural Electrical Energy Sources Variables

The sensitivity examination consists of studying the impact of different physical variables on the modeled system and analyzing the parameter variations that occur under climate and environmental changes. In addition, it evaluates the designed system effect regarding more than one case as cited in the literature, [4], [22], [23], [24], which reveals the selected system robustness through the examination of uncertain variables such as solar irradiation, biomass, and diesel price, [3]. In most of the cases, the doubt is considered in the energy resources and mentioned system components, [3], [25].

4 Modeling of Renewable Energy System's Components

In the current study, solar and wind are considered as the main primary sources of renewable energy systems. Annual Monthly solar radiation and wind speed data are obtained and simulated with the HOMER PRO software tool. The evaluation of the energy storage systems and resources is explicated in the following manner:

4.1 Solar Radiation and PV Modules Output Power

Based on the measured solar radiation and ambient temperature, The hourly energy output of solar modules can be computed using the following calculation, [22]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}}\right) \left(1 + \alpha_P \left(T_c - T_{c,STC}\right) \right. \quad (3)$$

where

Y_{PV} [kW]: represents the PV array's related capacity, or its output power under typical test circumstances (STC), which consist of radiation of 1 kW/m^2, cell temperature of 25 °C with no wind;
f_{PV}: is the PV derating factor;
G_T: is the solar radiation incident on the PV array in the current time step;
$G_{T, STC}$: is the incident radiation at STC;
α_p: is the temperature coefficient of power;
T_c: is the temperature of the PV cells in the current time step;
$T_{c, STC}$: is the temperature of the PV cells at STC.

According to the NASA website data resources, The annual average solar irradiation is 5.40 kWh/m^2/ day for the three villages.

4.2 Wind Speed and Turbine's Output Power

A turbine's main function is to convert the mechanical wind energy into electrical energy. Equation (4) represents a wind turbine's output power under normal pressure and temperature [3], in which the wind turbine's rated power, rated velocity, cut-in velocity, and cut-out velocity are indicated by the letters P_r, V_r, V_{cut-in}, and $V_{cut-out}$.

According to the diagram shown in Figure 2, the monthly average wind resource statistics for the chosen villages are provided from the NASA resource website. The annual average wind speed in the considered region is 3.57m/s.

$$P_{WT}(t) = \begin{cases} 0, & v(t) \le v_{cut-in} \text{ or } v(t) \ge v_{cut-out} \\ P_r \left(\frac{v^3(t) - v_{cut-in}^3}{v_r^3 - v_{cut-in}^3}\right), & v_{cut-in} < v(t) < v_r \\ P_r, & v_r < v(t) < v_{cut-out} \end{cases} \quad (4)$$

Where

P_r: is rated power, V_r<v(t)< $V_{cut-out}$
V_r: is the rated velocity
V_{cut-in}: is the cut-in velocity
$V_{cut-out}$: is the cut-in velocity

4.3 Hydrogen Energy Storage System Components

The energy storage system in the three villages is composed of an electrolyzer and green hydrogen tank as shown in Figure 1. Indeed, in most common off-grid systems, the batteries have emerged as beneficial devices to store the excess of the produced energy and create equivalence between the load demand and energy excess during low-demand periods. In addition, batteries can be used in off-grid and on-grid systems to reduce the intermediacy of renewable energy sources. Despite their significant role in storing energy, the green hydrogen storage technique has become a major competitor.

4.3.1 Electrolyzer

As a crucial device of the renewable energy production system, the electrolyzer is considered one of the most appropriate manner for green hydrogen production, [26]. It is divided into multiple types according to the practical usage. PEM and alkaline electrolyzers are the most commonly used due to the purity of hydrogen produced and also due to their low capital cost compared to other types, [27].

4.3.2 Hydrogen Storage Tank

The produced green hydrogen through an electrolyzer, is compressed and stored in a tank. The power required for the green hydrogen compression is expressed in the equation (5) as follows, [28]:

$$\mathrm{P_{comp}} = \left(\frac{\psi}{\psi - 1}\right) \times \mathrm{R} \times \left(\frac{\mathrm{T}}{\eta_c}\right) \times \left(\frac{\mathrm{P_2}}{\mathrm{P_1}}\right)^{\frac{\psi - 1}{\psi}} \times \dot{q}_{H_2} \quad (5)$$

Where

ψ: is the polytrophic coefficient;
R: is the gas constant;
T : is the compressor inlet temperature;
ηc: is the compressor efficiency;
P_1: is the inlet pressure;
P_2: is the outlet pressure;
$\dot{q}_{H_2}$: represents the mass flow rate of the green hydrogen.

The green hydrogen tank's pressure is defined below in the equation (6):

$$\mathrm{P_{tank}} = \frac{\mathrm{RT}}{\mathrm{V_{tank}}} \eta_{tank} \quad (6)$$

Where

η_{tank}: is the number of moles of gas in the tank;
V_{tank}: is the tank's capacity.

5 Technico-economic Data of the Studied Region

5.1 Site Description:

The three villages considered for study are TIZI, IGRDAN, and ASFOULA. They are located in the Demnate region in the AZILAL province of Morocco with an altitude of 960 meters above sea level and geographical coordinates of 29°49'51°N and 9°22'10°W. The three settlements are home to 140 families. They sit close together in the center of Montagne far from Marrakech city about 110 Km, where there are few transportation options and consequently few people, which impacts the population’s daily life.

The two main economic activities in these rural areas are agriculture and livestock husbandry. They are connected to the grid network. However, due to the geographical shape site, it is difficult to maintain a fluent energy flow and the use of an electrical grid network during the hot or cold seasons is financially exhausting for the population due to their low income. For these reasons, it is very crucial to find other ways to supply the three villages with cheap and independent electrical energy sources other than the grid network. Therefore, the main purpose of this study is to respond to this energy issue, based on an on-site visit, the community's needs and suitable solutions are selected.

5.2 Electrical Loads Assessment Used in the Study Area

The electrical demand assessment was carried out based on an on-site study in the village. The three villages' load demands are divided into three categories: basic household load, community load, and commercial load. Since the determination of the load demand is captured based on seasonal variations (air conditioning, fans, refrigerator …etc.), water pumping, schools, and mosques are all seasonal loads, so the basic household load is energy-consuming dominant compared to commercial and community loads. Table 1 (Appendix) shows the daily electrical power demand seasonally.

Most of the existing household loads are modest in the study area and don’t require high electrical energy by using grid extension due to its high cost. This encourages the integration of an optimized renewable energy system to respond to the community needs.

Table 1 (Appendix) illustrates the electrical power consumption of each household appliance during one day in the summer and winter seasons. As noted, one household needs 15,19kWh/day and 14,66kWh/day during winter and summer respectively. However, the total energy needed for the three villages is 2127,65 kWh per day and 253 kW as peak electrical power.

5.3 Design Specification and Component Choice

The designed hybrid renewable energy system is composed of solar modules and wind turbine generators as main sources, and the storage unit tank of hydrogen while the power converter is used to provide the electricity (current or voltage) for different load types from DC to AC. The hydrogen tank serves as a storage unit to guarantee the stability of the output electrical power given to the loads. As for the electrolyzer, it uses electricity to split water into hydrogen and oxygen, while its load is inserted to measure the efficiency of the hydrogen tank. Indeed, the grid modules were taken into consideration in the design phase to compare the economic impact of off-grid systems with hydrogen and on-grid systems with hydrogen storage. Additionally, a generator is inserted as a source of energy to prevent the problem of renewable energy source intermediacy. The majority of economic data input of the designed component is selected from the HOMER software database. As shown in Figure 1, multiple components were selected to constitute the architecture of the optimized suggested system. The following paragraph describes the inserted parameters of the selected system components.

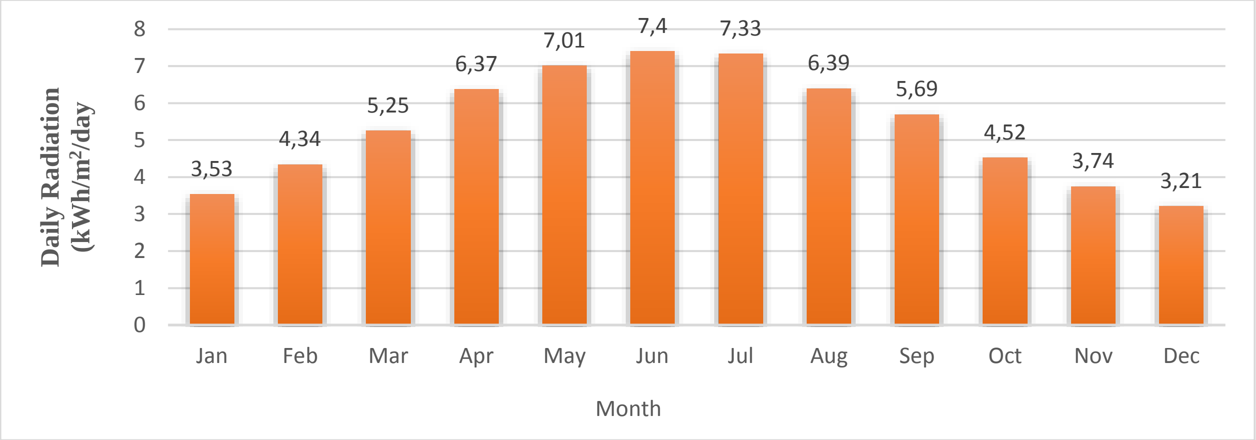
5.4 Solar Power Generator Modules

The PV power generator is connected to the DC bus with a lifetime of 25 years. From the HOMER software database, a generic flat plate PV is selected with a capital cost of 2500$ for 1 kW, 2500 $ as a replacement cost while the O&M cost considered is 10$/year. In addition, about 80% is thought to be the derating factor of each PV panel. Nevertheless, the number of PV panels opted to generate the power is determined by the Homer optimizer feature.

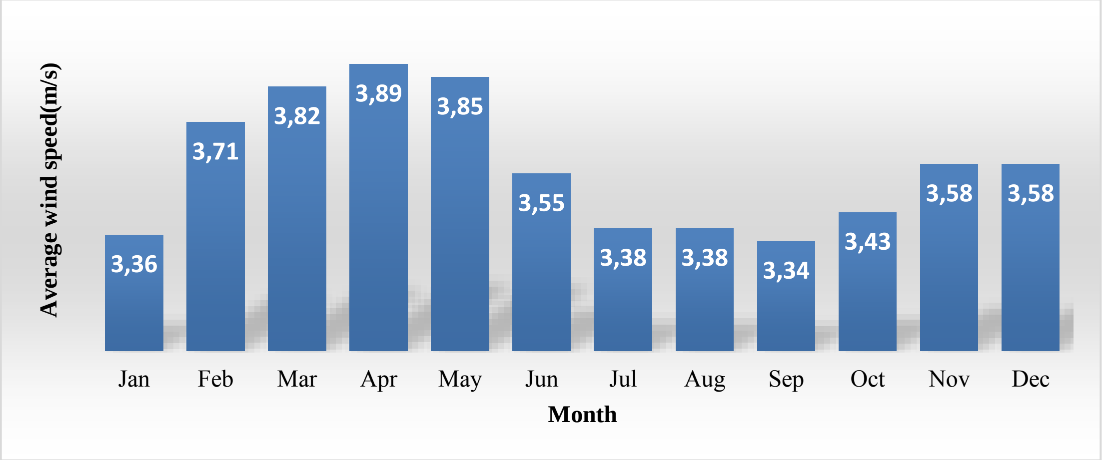
5.5 Wind Power Generator Turbine

Like the PV generator selection, the wind turbine power generator type selection is done by referring also to the HOMER software database. The wind is connected to the AC bus. A generic 3 kW (G3) is selected with a lifetime of 20 years and a hub height of 17m. The capital cost of one unit of G3 is fixed at

18000$ while the considered replacement cost is 18000$ and the O&M cost is 180$/year.



(a) Monthly solar Global Horizontal Irradiance changes



b) Monthly wind speed changes

Fig. 2: Diagram of natural energy resources changes

5.6 Generator

An Autosize Genset is selected to provide backup power in the designed system. It sizes itself automatically to meet the load requirement. The initial capital cost and the replacement cost of the auto-size Genset are equal to 500$/ kW while the O&M cost is 0.030$/op.hour. The generator is connected to the DC bus with a lifetime of 1500 operating hours and the minimum load ratio is set to be 20%.

5.7 Power Converter

The power converter is used to provide the AC outputs from the DC source to meet the load requirement. The selected type is a generic system converter with a lifetime of 15 years. Its efficiency and relative capacity are 95% and 100% respectively while the capital and replacement cost of 1kw is 300$.

5.8 Electrolyzer

The electrolyzer is linked to the DC side, the selected electrolyzer is a generic electrolyzer with a 15-year lifetime, with a capital cost of 1100$ for one kW, a replacement cost of 850$, and an O&M cost of 10 $/year. As for its capacity optimization, it varies between 0 kw to 800 kW and its efficiency is approximately 85%. The economic data is obtained by referring to the literature, [26].

5.9 Hydrogen Tank

A generic tank is selected to store the hydrogen produced by the designed systems with a lifetime of 25 years. The capital cost of 1kg produced hydrogen is 1000 $ while its replacement cost goes to 750 $ and the capacity optimization of the storage tank varies from zero kg to 900 kg. Its relative size is set to 50 %.

5.10 Project and Grid Economic Estimation

This project has estimated that the designed EES lifetime is managed to be 25 years with an inflation rate of 2% and a discount rate of 8%. A grid extension is taken into account to ensure the reliability of the considered system and to study the possibility of off-grid system implementation on the mentioned site. In fact, the grid extension capital cost is 8000 $/km while the grid power price is 0.10 $/kWh.

6 Results

Based on the data inserted into the HOMER software program and by referring to its selected system's components, including the consumption rate of energy, the simulation was carried out to study the suitable system to feed the considered region with a clean environment and low-price electrical energy for the next 25 years.

The obtained simulation results are responding to the load demand requirement, with 2127,65 kWh per day, and peak power of 253 kW, and a separate hydrogen load to manage the efficiency of hydrogen storage, giving two major options both of which are off-grid systems with an analysis of the grid extension.

6.1 First Option

The first alternative system architecture is depicted in Table 2. The optimized system is constituted of a power source PV-Generator with 3759kW and 300kW provided by the Autosize Genset generator whereas the DC/ AC power converter supplies about 317kW of electrical energy for loads and finally 800kW is produced by the generic electrolyzer while the hydrogen tank storage capacity reaches 900Kg.

As expressed in equations (1) and (2), the determined LCOE revealed in Table 2 of the system is 1.56$/kWh and the NPC cost is 15.6M$. Moreover, Figure 3 illustrates the cost summary for each component while Table 3 provides more details by indicating the different charges of each component including its capital cost, replacement cost, O&M cost, fuel cost, salvage cost, the total cost of the component and finally the total cost of the whole system configuration. As a result, the generic flat plate of the PV generator is indicated as the most expensive component in this system architecture while the cheapest component is the power system converter. However, by focusing on the electrical energy production presented in Figure 4, it is clearly shown that the mentioned PV generator provides about 92.5% of the total energy production while the Autosize Genset generates only 7.53% of the total energy supplied to the load. So, the majority of the electrical energy is generated by PV sources (generic flat plate PV) which justifies the high cost of PV generators compared to the other renewable energy system components.

Table 2. System Configuration for the first option

Component	System configuration	
	Size	Unit
PV- Generator	3759	kW
Autosize Genset-Generator	300	kW
Power Converter	317	kW
Electrolyzer	800	kW
hydrogen tank capacity	900	kg
LCOE	1.56	$/kWh
Dispatch strategy	Homer Cycle Charging	

Under typical working conditions, the output load is supplied by the PV power generator, and any extra energy is delivered into the electrolyzer to produce hydrogen. According to the results presented in Table 4, the AC primary load consumes 21.8% of the energy produced while 78.2% of the energy is consumed by the electrolyzer. Moreover, based on the high energy consumption rate of the electrolyzer, 59960 kg of green hydrogen is produced per year as described in Table 5.

To evaluate the effectiveness of green hydrogen storage and the possibility of using its tank to feed electricity to other loads, hydrogen is taken into account. The measurement shows that the hydrogen load consumption reaches 60338kg/year with no excess.

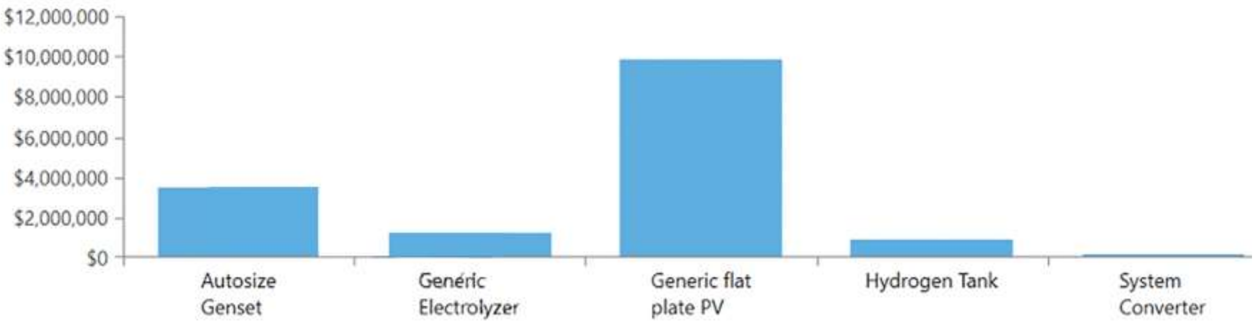


Fig. 3: Diagram of the system components summary cost

Table 3. Detailed cost of the system architecture

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Autosize Genset	150000.00	625805.93	626299.39	2089868.79	1018.12	3490955.99
Generic Electrolyzer	880000.00	288506.20	103420.13	0.00	54299.78	1217626.56
Generic flat plate PV	9396378.47	0.00	485887.30	0.00	0.00	9882265.77
Hydrogen Tank	900000	0.00	0.00	0.00	0.00	900000
System Converter	95229.43	40403.35	0.00	0.00	7604.32	128028.47
Total System	11421607.90	954715.49	1215606.83	2089868.79	62922.22	15618876.79

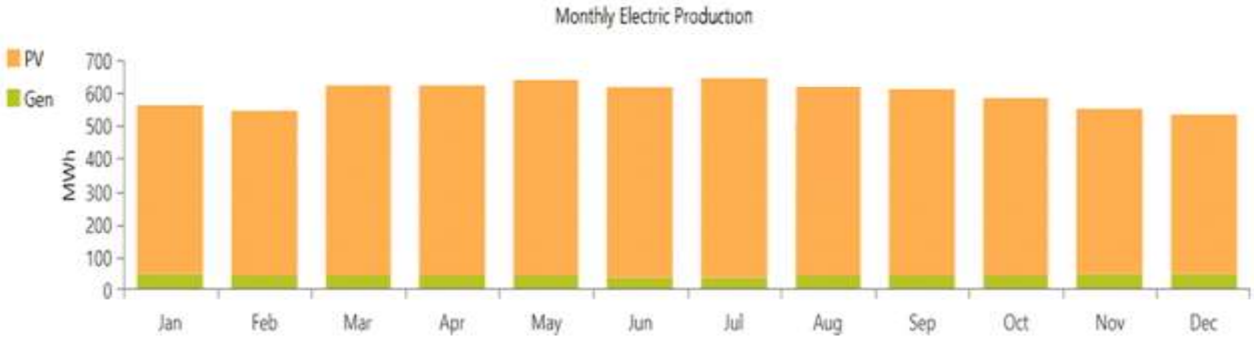


Fig. 4: Distribution of electrical power generation

Table 4. Electrical energy consumption

Consumption	kWh/yr	%
AC Primary Load	776592	21.8
Electrolyzer Consumption	2782458	78.2
Total	3559050	100

Table 5. Electrolyzer production capacity

Production	kg/yr	%
Electrolyzer	59961	100
Reformer	0	0
Total	59961	100

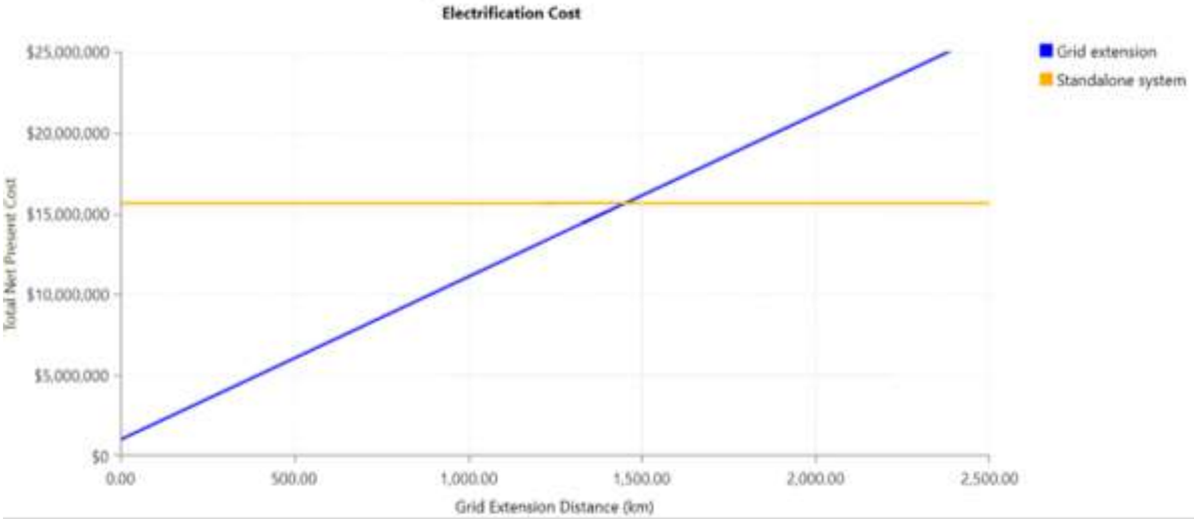


Fig. 5: Net Present Cost of the grid extension compared with the off-grid option

6.1.1 Grid Extension

Figure 5 presented below depicts the comparison of (NPC) between off system and the grid extension depending on the grid distance. The obtained curves demonstrate that the cost of an off-grid system is constant even if the grid extension distance increases. However, the cost of grid extension is consequently increasing with the grid extension distance. For distances below the break-even point (1451.56 km), the grid extension cost is lower than the off-grid system cost. Otherwise, the grid extension is very expensive for distances above the break-even point.

6.2 Second Option

The second proposed option designed to produce electrical power in the considered region, shown in Table 6, is a system combined of 3743kw of PV generator, seven G3 (3kW) wind turbine generator, 300kW of Autosize Genset, 323kW of power system converter, 800 kW of generic electrolyzer and 900kg of hydrogen storage tank.

Table 6. System Configuration

Component	System Configuration	
	Unit	**Size**
Generic flat plate PV	kW	3743
Generic 3kw		7
Autosize Genset	kW	300
Power System converter	kW	323
Generic E electrolyzer	kW	800
Hydrogen Tank	kg	900
Dispatch	Homer CC	

The financial analysis obtained in Table 7. The LCOE of the system is about 1.57$ while the NPC of the system reaches 15.7M$. It also specifies the cost of each component used in the system such as the capital cost, replacement cost, O&M cost, fuel cost, salvage cost, the individual component's total cost, and finally the whole system's total cost. Indeed, according to the diagram of the NPC of each component shown in Figure 6, it is noticed that the generic flat plate PV generator is the most expensive followed by the Autosize Genset. However, the domination of PV generators in electricity production in the two cases (unlike the wind generator) is due to the meteorological conditions in the DEMNATE region where the solar irradiation is higher than the wind speed, in addition to the geographical situation of the region which is generally mountain and due to the facility of its implementation, unlike wind generators, all these conditions favor the effectiveness and use of PV generators. As a result of the study, according to Figure 7 and Table 8, the electrical energy produced by the three generators: PV, Autosize Genset**,** and wind turbines are respectively 6587092kwh/year, 536280kwh/year and 9599 kwh/year which represent 92.3%, 7.52%, and 0.135% of the total energy production respectively. Therefore, 31.8 % of the energy is generated only by renewable energy systems and delivered to the loads. The Ac primary load consumes about 21.8% while 78.2% is consumed by the electrolyzer as shown in Table 9.

Consequently, according to the results obtained in Table 10, the green hydrogen production through the electrolyzer is 59961 kg per year. The consumption of green hydrogen load during one year reaches 60337 kg per year likewise the quantity revealed in Table 11 with no hydrogen excess, which means that it responds to load demand with 60337kg, including the AC primary load served by the basic renewable energy system proposed.

Table 7. The detailed cost of the system architecture

Component	Capital ($)	Replacement ($)	O&M($)	Fuel($)	Salvage($)	Total($)
Autosize Genset	150000	625669.40	626066.70	2083072.79	(1137.90 $)	3483670.99
Generic 3 kW	126000	40169.73	16288.67	0.00	22638.22$	159820.18
Generic Electrolyzer	880000	288506.20	103420.13	0.00	54299.78	1217626.56
Generic flat plate PV	9356513.82	0.00	483826.01	0.00	0.00	9840339.83
Hydrogen tank	900000	0.00	0.00	0.00	0.00	900000
System converter	96770.32	41057.11	0.00	0.00	7727.36	130100
Total System	11509284.14	995402.44	1229601.51	2083072.79	85803.26	15731557.63

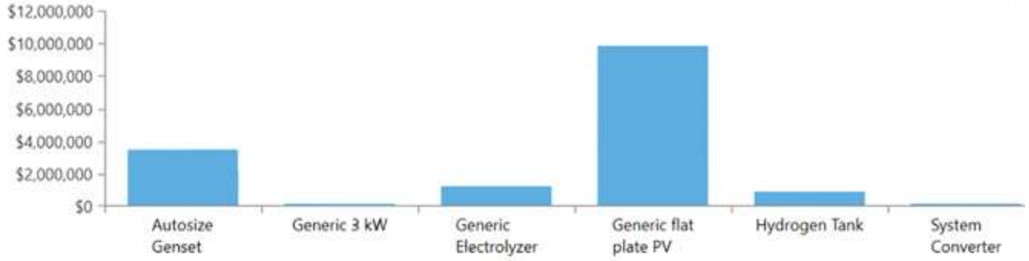


Fig. 6: Diagram of the system component's summary cost for the second option

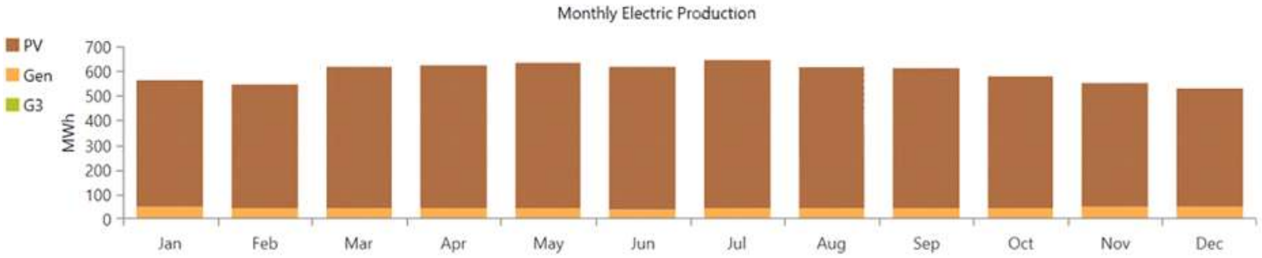


Fig. 7: Distribution of monthly electrical power generation

Table 8. Electrical energy production

Production	kWh/yr	%
Generic flat plate PV	6587092	92.3
Autosize Genset	536280	7.52
Generic 3 kW	9599	0.135
Total	7132972	100

Table 9. Electrical energy consumption

Consumption	kWh/yr	%
AC Primary Load	776592	21.8
Electrolyzer Consumption	2782487	78.2
Total	3559079	100

Table 10. Electrolyzer production

Production	kg/yr	%
Electrolyzer	59961	100
Reformer	0	0
Total	59961	100

Table 11. Hydrogen Consumption

Consumption	kg/yr	%
Hydrogen load	60337	100
Total	60337	100

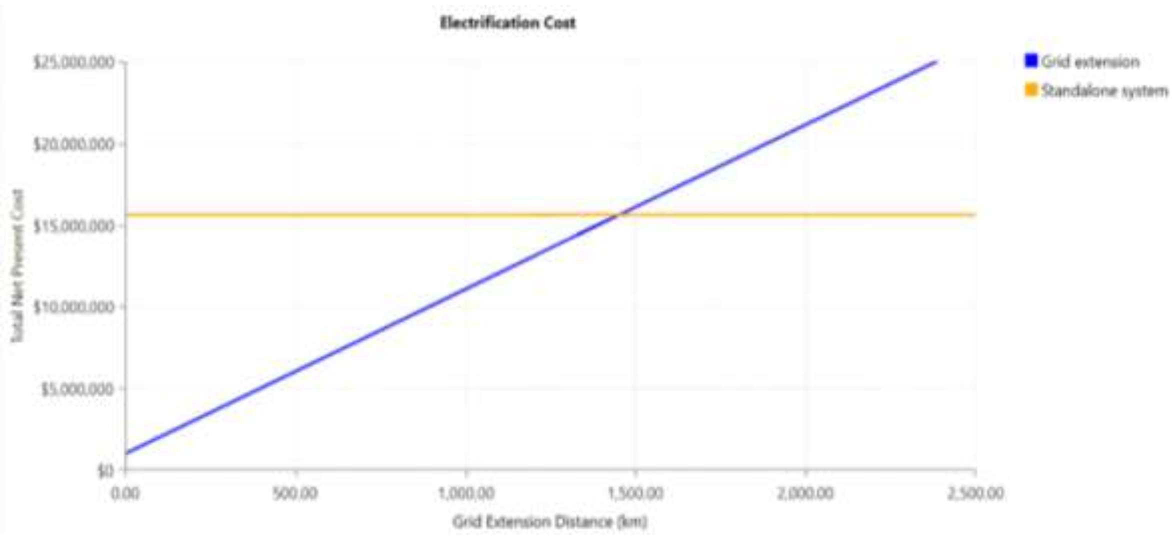
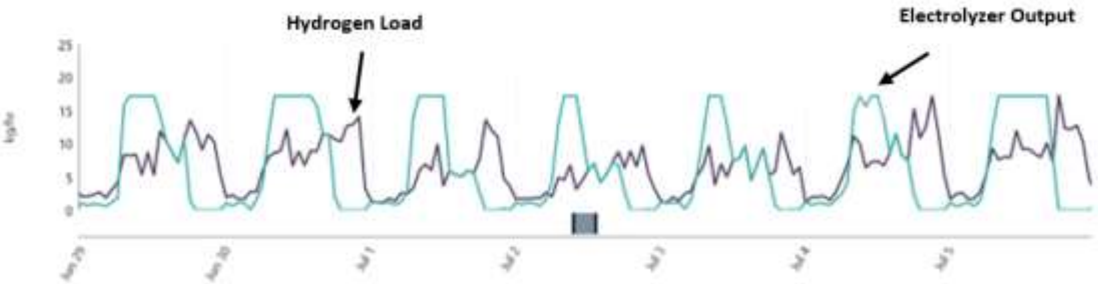
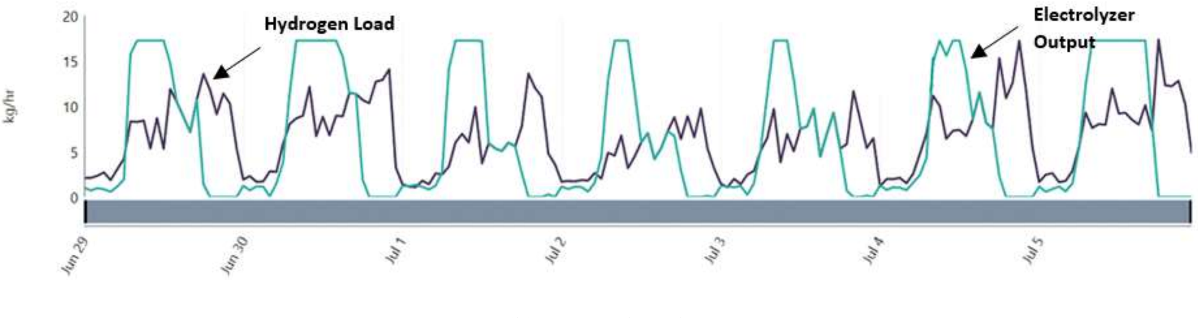


Fig. 8: Diagram of the NPC of the grid extension compared with the off-grid for second option



(a) First option



(b) Second option

Fig. 9: Diagram of monthly green hydrogen load served and electrolyzer Output

These results prove the ability of rural areas to play an important hub in clean and economic energy to generate and store large quantities of PV- hydrogen production to be used and exported to other areas like cities.

6.2.1 The Grid Extension of the Second Option

As previously explained in the first option, Figure 8 illustrated below depicts the comparison of the NPC between off-grid system and the grid extension depending on the grid distance grid extension. It displays that the grid extension distance is proportionally increasing while the off-grid system cost is constant and does not depend on the grid extension distance. For distances below the break-even point (1426.76 km), the grid extension cost is lower than the off-grid system. Otherwise, the grid extension is very expensive for distances above the break-even point.

As presented in Figure 9, the monthly variation of the hourly amount of the hydrogen load served and the electrolyzer output during the period between June and July. For both cases, the electrolyzer output exceeds 15kg/hr especially in the duration of July. As for the provided green hydrogen load, it is generally less or equal to the electrolyzer output. Therefore, the hydrogen load is fully supplied through the electrolyzer, including the AC primary load which is powered by the Off-grid system without involving electrolyzer consumption and hydrogen production. It could be considered an exportation spot for other cities when there is no need for hydrogen load in rural areas. On the other hand, the designed off-grid system has proved its ability to feed the AC primary load and to produce simultaneously 15 kg/hr for accumulating the hydrogen in the storage tank.

7 Discussion

To evaluate the accuracy of the result, a comparison between current results and literature results is done. The designed systems in this paper prove the feasibility of powering three villages with electricity using PV modules, auto-size generators, and wind turbines. Both systems rely on the PV modules as the main generator of electricity and green hydrogen. Similarly, the LCOH of the energy production in the Dakhla region based on the PV plants reaches 17 cents / Kwh, [29]. In [5], the author studies the off-grid hybrid renewable energy system implementation with hydrogen storage. The LCOE represents 2.34 $/kWh which is higher than the LCOE found in this study (1.57 $/kWh and 1.56$/kWh for the first and second systems).

8 Conclusion

Studying the feasibility of integrating an off-grid system with hydrogen generation is extremely important to guarantee fluent electrical energy in cities and rural areas. The African continent has a qualified potential for renewable energy sources that could upgrade the economic and social aspects of African countries if it is well exploited. The Moroccan government, by announcing the road map towards renewable energy systems integration, have already given the start of the new energy transition in different areas of the country. In the same context, some efforts have been made to give importance to green hydrogen production. This paperwork examines the feasibility of integrating RES with hydrogen production in rural areas. It aims to compare between the grid extension and off-grid system integration in the considered area “DAMNETE” region by using the HOMER software tool to modulate and simulate the optimized system and based an on-site visit, the load was determined. The simulation results prove the possibility of implementing two off-grid systems with hydrogen generation. The first system is constituted of a PV generator, an electrolyzer, a green hydrogen storage tank, system of power converter while the second system takes into account the integration of seven G3 wind turbines. Both systems have effectively fed the AC primary load while the electrolyzer consumes the rest of the produced energy to produce the green hydrogen with an LCOE lower than 1.6$/kWh.

The hydrogen load is fed completely with 15kg/hour, which allows exporting the excess amount not needed in rural areas. As a result of the study, due to the geographical conditions of the region, a PV generator is more recommended than a wind turbine because of its high productivity and the high solar irradiation compared to the wind speed. Therefore, the large space of rural areas can be exploited to build green hydrogen production centers and helps also reduce the economic and demographical pressure. From a perspective, it is recommended to implement the designed systems in the current study in reality to validate the results.

Index of Abbreviations

RES	renewable energy systems
ESS	energy storage systems
PHS	pumped hydro storage
CAES	compressed air energy storage
TES	thermal energy storage
EMES	electrostatic and magnetic energy storage
ELMES	electrochemical energy storage
LCOE	levelized cost of energy
NPC	Net Present Cost
O&M	Operating and maintenance expenses

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APPENDIX

Table 1. Daily electrical power consumption of one household

Load of household appliances	**Power rating (W)**	**N°. In use**	**Summer (March to October)**		**Winter (November to February)**	
			Operating time (h/day)	**Wh/day**	**Operating time (h/day)**	**Wh/day**
Light	85	9	10	7650	11	8415
Table fan	45	1	2	90	0	0
Iron	1400	1	0,25	350	0,15	210
Computer	200	1	5	1000	5	1000
TV	200	1	6	1200	6	1200
Refrigerator	125	1	24	3000	24	3000
Water pump	1750	1	0,75	1312,5	0,75	1312,5
Mobile charger	5	4	3	60	3	60
Total power (W)				14662,5		15197,5

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- EL HAJI Ikram: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization.
- Kchikach Mustapha: Writing – original draft, Writing – review & editing, Visualization, Project administration.
- Abdennebi EL hasnaoui: Supervision, Project administration.

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