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Conference paper

On-Grid Hybrid PV/WT Renewable Energy System for Green Hydrogen Production

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ABSTRACT

The term "Power-to-X" (PtX) refers to a set of techniques for converting electrical energy into another form of energy, primarily focusing on hydrogen production. Produced hydrogen can be stored, distributed, and then used directly (to regenerate electricity, generate heat, or in transportation, steel, and chemical industries) or indirectly to produce ammonia, fertilizers, methane, methanol, e-fuels, and more. Thus, PtX is a mean of storing intermittent energy and a key contributor to the energy transition and decarbonization. In this article, we examine a grid-connected green hydrogen production system. This 1 MW renewable capacity system consists of a 300 kW wind turbine, a 700 kW photovoltaic field, and a 209 kW electrolyzer. In this system, any excess energy is integrated into the grid, enhancing overall energy sustainability. Conversely, when energy output is insufficient for the electrolyzer, the deficit is sourced from the grid, ensuring continuous and reliable operation. This dynamic interaction with the grid optimizes energy usage and reinforces the stability of the system. The results show an annual hydrogen production of about 16 tons, renewable energy production of approximately 1.9 GWh/year, a 20.85% capacity factor, a shortage of about 144.5 MWh, and an energy excess of about 824 MWh.

1. INTRODUCTION

Environmental challenges and dangers associated with the global demand for energy—such as the growing of this demand, the effects of greenhouse gases, global warming, climate change, and the depletion of traditional energy sources—have in-cited policymakers to adopt the 'energy transition' to more sustainable energy. This transformation involves the gradual replacement of the contribution of

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fossil fuels in the energy mix with renewable energies. Green hydrogen appears to be an ideal candidate to replace fossil fuels and to support the intermittent renewable sources.

Hence, global hydrogen consumption is growing constantly, 95 Mt in 2022 (an increase of almost 3% year-on-year), it is mainly driven by traditional applications; while new applications like power generation remain minimal (IEA, 2023).

However, the main method of producing hydrogen remains polluting and energy-intensive. Thus, sustainable hydrogen production techniques such as water electrolysis based on clean energies are inevitable. Despite higher costs, renewable hydrogen is expected to play a crucial role in the Net Zero scenario, 2022-2050, and will account for around two thirds of total demand by 2050, which will reach 614 Mt (IRENA, 2022).

Algeria is endowed with a tremendous potential in terms of renewable energies, which makes it a prime candidate to meet the both local market and Europe demand for green hydrogen. In fact, Algeria has the highest solar energy potential in the Mediterranean region with a capacity of 16,555.48 TWh, and 443.96 TWh only on its coastal area (Stambouli et al., 2012). Beyond solar energy, Algeria's wind potential is around 35 TWh/year (Benasla et al., 2024) with wind speeds of over 8 m/s across its 1,300 km Mediterranean coastline.

The use of hybrid photovoltaic/wind (PV/WT) systems exploits the complementarity between the two sources to produce energy and hydrogen in a stable, continuous and reliable manner with the possibility of reducing the cost (Tang et al., 2022), and projections stated that photovoltaic and wind could dominate the world's energy supply by 2050 (Lowe & Drummond, 2022). Despite the complementary of these two sources, they remain variable and intermit-tent. Hence, energy storage solutions and grid integration are required. On-grid renew-able energy systems are bi-directional; the grid plays the role of a storage system and provides electricity when needed or absorbs excess electricity. Moreover, a study demonstrated the importance of the on-grid option in green hydrogen production (Tang et al., 2022).

This article presents a study on a configuration of a pilot green hydrogen production system. The system primarily comprises a photovoltaic field, a wind turbine, the electrical grid, and an alkaline electrolyzer. Alkaline technology is chosen despite its lower efficiency because of its maturity, proven technology, bankability, and the use of PGM-free catalysts. In fact, one-hour time resolution data for a typical meteorological year (TMY) from a site in northwest Algeria (Arzew) were obtained from Meteonorm and used.

2. MATERIALS AND METHODS

2.1 Site Description

This work was carried out on Arzew (35.856, -0.313, on the western coast of Algeria), a site close to the sea—a source of water for electrolysis—a refinery, and a urea and fertilizer factory. This site is characterized by an average annual wind speed of 3.23 m/s and an insolation duration of approximately 1900 hours (low compared to the average annual sunshine duration on the Algerian coast, which is 2,650 hours (Stambouli et al., 2012)). Table 1 provides statistical summaries of the seasonal and annual wind speed at a height of 10 m, and insolation duration at this site. It should be noted that the average annual wind speed increases to 4.46 m/s at the hub height of 100 meters, given a site wind shear coefficient of 0.14.

Figures (1) and (2) illustrate the monthly global radiation on a horizontal plane and the monthly average wind speeds at an altitude of 10 meters.

Table 1. Statistical summaries of the renewable sources

	Wind speed (m/s)	**Insolation Duration (h)**
Yearly	3.23	1891.06
Winter	2.58	320.75
Spring	**3.91**	592.66
Summer	3.38	**652.53**
Autumn	2.90	325.11

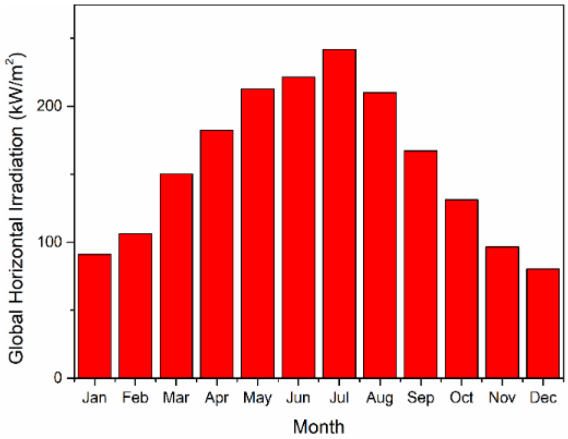

Fig 1. Available monthly solar energy

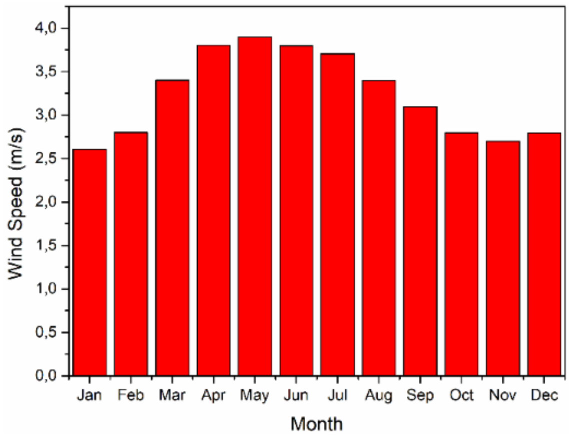

Fig 2. Monthly site wind speed

2.2 System Design and Modeling

2.2.1 System description

The studied system simulates a hybrid pilot system connected to the grid. It consists of a combination of two solar and wind energy converters, a photovoltaic generator, and a wind turbine, connected to the grid and supplying an electrolysis system for green hydrogen production.

Energy management is considered as follows: the renewable energy produced powers an alkaline electrolyzer. If this energy exceeds the nominal energy of the electrolyzer, the excess is injected into the grid via a DC/AC converter. However, if the energy is less than the minimum energy required by the electrolyzer (30% of the nominal power, 62.7 kW in our case), the deficit is imported from the grid via an AC/DC converter to keep the electrolyzer on standby.

The studied system consists of the following:

- A 300 kW NordTank wind turbine (WT), selected from seven wind turbines, with different nominal power NP, due to its superior capacity factor (the ratio of actual production to maximum potential production over a year), as shown in Table 2;
- A 700 kWp photovoltaic (PV) system, fixed, inclined at the site's latitude, and oriented due south, this increased the captured radiation by 15.62%, particularly during the autumn and winter periods;
- A 209.25 kW nominal power alkaline electrolyzer (155 cells of 1.35 kW each).

The system includes two DC-DC converters for photovoltaic energy: an MPPT converter with an efficiency of 0.98 and a Buck converter with an efficiency of 0.95. Additionally, we took into consideration an AC-DC converter for wind energy with an efficiency of 0.98. It should be noted that the height of the wind turbine is considered 100 meters and the capacity factors (CF) of the PV system alone, the wind turbine alone, and the hybrid system before and after power conversion are about 21.9 %, 22.38%, 22.04% and 20.85%, respectively.

Table 2. Capacity factor (CF) of seven wind turbines

WT	Enercon	**NordTank**	Bonus	Enercon	Enercon	Vestas	Bonus
NP (kW)	230	**300**	300	500	600	1650	2000
CF (%)	15.32	**22.38**	16.56	14.72	16.10	11.88	13.33

2.2.2 System modelling

The mathematical models of the main components of the studied system—alkaline electrolysis, wind turbine, and photovoltaic cell—are given below. The first model provides the IV curve of a solar cell depending on the light current I_L, diode current I_D, and the shunt current I_{sh}. The second model describes the power output of wind turbines. Finally, the third equation presents the UI curve as a function of temperature, detailing the electrochemical model of an alkaline electrolysis cell (Calderón et al., 2010; Duffie & Beckman, 1991; Kabouche et al., 2021; Khalilnejad et al., 2018; Ulleberg, 2003).

$$I = I_L - I_D - I_{sh} = I_L - I_0\left[exp\left(\frac{U + IR_s}{a}\right) - 1\right] - \frac{U + IR_s}{R_{sh}} \quad (1)$$

$$P = {}^{1}/_{2}\, \rho\, A\, V^3\, C_p \quad (1)$$

$$U = U_{rev} + \frac{r_1 + r_2 T}{AREA} I + (S_1 + S_2 T + S_3 T^2) log\left[\frac{t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}}{AREA} I + 1\right] \quad (2)$$

$$\eta_f = \left[I_{density}^2 / \left(a_1 + I_{density}^2\right)\right] a_2 \quad (4)$$

Where: R_s, R_{sh} are series and shunt resistances [Ω]; ρ is the air density (kg.m^{-3}), A is the swept area (m^2), V is the wind speed (m/s), and C_p is the coefficient of performance of the wind turbine; r_i represents the ohmic resistance of the electrolyte (Ω.m^2); S_i, t_i are the overvoltage coefficients, which depend on temperature; a_1 (mA^2/cm^4), and a_2 are parameters in faraday efficiency calculation.

3. RESULTS

Figure 3 shows the monthly production of three configurations of the 1 MW system. The first configuration consists of 30% wind energy and 70% photovoltaic energy, the second consists of 60% wind energy and 40% photovoltaic energy, and the third consists of 90% wind energy and 10% photovoltaic energy. The first configuration was chosen for its superior performance during the most unfavorable months and seasons of autumn and winter. Even, the annual production of the three configurations is as follows: 1931.45 MWh, 1944.10 MWh, and 1956.75 MWh, respectively.

Figure 4 presents the energy balance of the system in MWh throughout a year. While, the energy deficit needed to ensure the operation of the electrolyzer in standby mode is imported from the grid; any surplus renewable energy exceeding the nominal capacity of the electrolyzer is injected back into the grid. Renewable energy produced within the range between the minimum and the surplus is directed to the 155-cell alkaline electrolyzer.

Regarding the graph representing photovoltaic energy production, we observe that the influence of solar radiation, captured by the solar panels, is greater than that of temperature and wind speed for most months. Consequently, the photovoltaic energy curve closely follows the solar radiation curve. Thus, most favorable months for energy production are July, August, and April, while the least favorable months are December, January, and November.

As for the graph representing wind energy production. The months of May, March, and June show peaks in production, which can be attributed to favorable wind conditions during these periods. Conversely, the months of November, January, and February display the lowest production, with values around 1.2 MWh. These decreases can be explained by periods of weaker wind.

Consequently, the total energy production of the hybrid system follows the pattern of wind energy production, despite wind energy representing only 30% of the nominal power. This is due to the high variability of wind energy, which can sometimes contribute up to 100%, especially at night. In contrast, photovoltaic production forms a nearly flattened bell curve with low variability. Thus, the months of May, July, and June show production peaks, with values reaching 6.1, 6, and 5.8 MWh, respectively. Conversely, the months of November, December, and January show the lowest production, with values around 4.4 MWh.

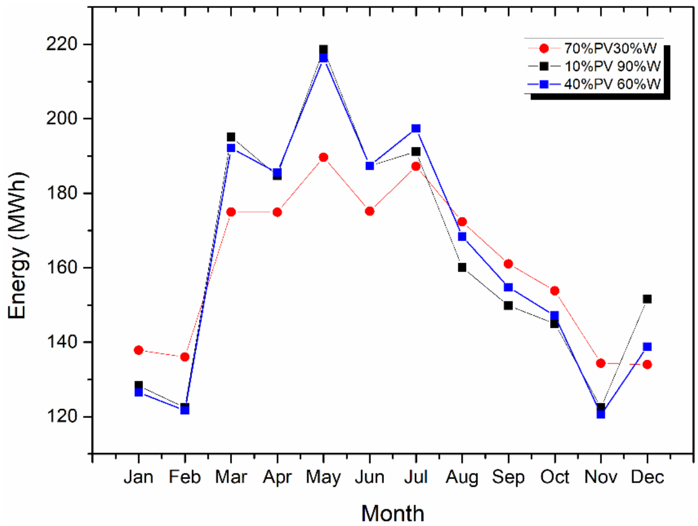

Fig 3. Monthly energy production of three configurations of the 1 MW system

Table 3. Summary of the annual and seasonal results data

	Renewable Energy	Wind Energy	PV Energy	To Electrolyzer	From Grid	To Grid	Hydrogen Production
	MWh						kg
Annual	1826,97	588.29	1343.16	1147,50	144.47	823.94	15948.73
Winter	405,65	*125.03*	303.81	*270,81*	*40.96*	*175.80*	3576.44
Spring	**510,45**	**181.78**	357.86	303,07	**29.27**	**236.65**	**4444.98**
Summer	500,90	149.95	**379.59**	**307,67**	35.71	228.94	4379.13
Fall	409,96	131.52	*301.88*	265,95	38.52	182.53	*3548.17*

Table 3 presents the annual and seasonal energy balance of the studied system. The renewable energy production, after accounting for losses due to the power stage, is low during winter and autumn but high during spring and summer. This variation is attributed to the potential and quality of the renewable energy sources, specifically solar radiation and wind, available at this site. Thus, the energy deficit corresponds to unfavorable seasons, while the excess corresponds to favorable seasons.

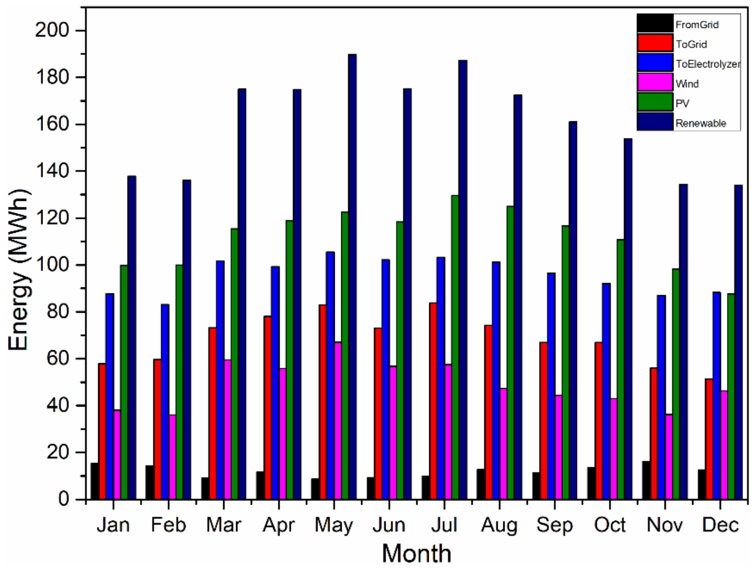

Fig 4. Monthly energy production and consumption

Figure 5 illustrates the energy transmitted to the electrolyzer and the monthly hydrogen production. Considering the number of days in each month, the production peaks occur in May, June, and March, with values around 50 kg/day. Conversely, January, November, December, and February show the lowest production, with values ranging from 34.81 to 38.26 kg/day. Moreover, according to Table 3, spring is the optimal season.

We found that the electrolyzer is in standby mode for 41.45% of the time, equivalent to 3,631 hours out of 8,760 hours. This percentage increased to 54.3% in January and decreased to 30.5% in March. This study also showed that hydrogen production ranged from 52.21 to 58.98 kWh/kg, with an average of 57.18 kWh/kg.

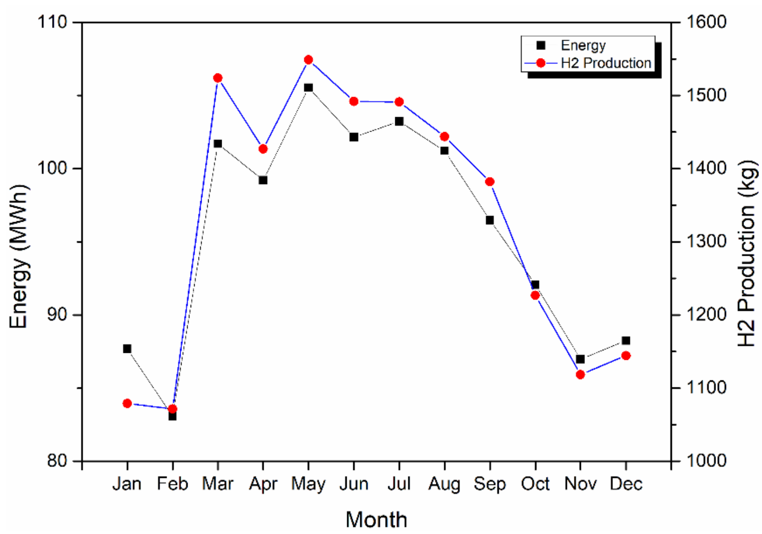

Fig 5. The monthly energy transmitted to the electrolyzer and estimated hydrogen production

4. CONCLUSION

This study focuses on the production of green hydrogen using a hybrid system composed of 70% PV and 30% wind, connected to the grid at the Arzew site in northern Algeria. This location is highly promising for Power-to-X, with a primary focus on hydrogen production. Its proximity to the sea provides a water source for electrolysis and facilitates the transport of excess hydrogen. Additionally, the site's closeness to a refinery and a urea and fertilizer plant supports the stationary use of hydrogen, eliminating the need for transport.

Therefore, the advantages of grid-connected Hybrid Renewable Energy Systems (HRES) include their stability, complementarity, and cost reduction through maximized energy production. These systems do not require energy storage, minimize energy waste, and limit energy interruptions.

Then, developing and implementing such pilot systems allows for the evaluation of technical and economic feasibility, identification and resolution of challenges, and serves as platforms for training and data collection, paving the way for larger systems.

The results indicated that this hybrid system produced 15,948.73 kg of hydrogen, with an annual average of 57.18 kWh/kg and a low capacity factor of 20.85%. As a perspective, it is essential to study the complete value chain, optimize the system, and conduct a technical-economic analysis. Additionally, exploring offshore sites could enhance the wind energy capacity factor compared to land-based sites.

NOMENCLATURE

A	Swept area [m^2]	r_i	Ohmic resistance of the electrolyte [$\Omega.m^2$]
CF	Capacity factor []	R_s	Series resistance [Ω]
C_p	Coefficient of performance of the wind turbine	R_{sh}	Shunt resistance [Ω]
I_D	Diode current [A]	S_i, t_i	Overvoltage coefficients []
I_L	Light current [A]	V	Wind speed [m/s]
I_{sh}	Shunt current [A]	ρ	Air density [$kg.m^{-3}$]
NP	Nominal Power [kw]		

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