Euro-Mediterranean Journal for Environmental Integration
https://doi.org/10.1007/s41207-024-00491-6

ORIGINAL PAPER

Technical analysis of exploiting untapped wind power for sustainable hydrogen energy production

Khaoula Adeli[1] · Mourad Nachtane[2] · Hassan Naanani[2] · Khadija Taroual[1] · Mahmoud ElMouden[3] · Dennoun Saifaoui[1]

Received: 15 November 2023 / Accepted: 13 February 2024

Abstract

This research explores the untapped potential of harnessing Morocco's abundant wind resources for sustainable hydrogen production. Through a meticulous examination of a comprehensive dataset detailing wind patterns in Moroccan cities and thorough scrutiny of the technical aspects of wind-to-hydrogen systems, our study unveils compelling evidence that these cities possess significant untapped wind power potential for hydrogen generation. What sets this potential apart is its feasibility without incurring additional costs, positioning it as a practical pathway toward achieving energy sustainability and mitigating greenhouse gas emissions in the region. The study offers valuable insights into the viability of integrating wind power and hydrogen production to foster a more environmentally friendly energy landscape in Morocco. Our findings reveal that, on an annual basis, electricity generation for specific locations, namely Tangier, Tetouan, and Essaouira, amounts to 9.96 GW, 2.93 GW, and 19.78 GW, respectively. Correspondingly, the annual hydrogen production at these locations stands at 180.41 tonnes for Tangier, 53 tonnes for Tetouan, and 358 tonnes for Essaouira, underscoring the considerable potential for clean energy generation and hydrogen output. This research not only identifies the untapped wind power potential in Moroccan cities but also establishes a clear link between wind power and sustainable hydrogen production. The presented evidence supports the feasibility of implementing this integrated approach as a practical and cost-effective means of advancing Morocco's journey towards a more sustainable and environmentally conscious energy future.

Keywords Wind energy · Energy integration · Hydrogen production · Technical evaluation · Potential of Moroccan cities

Abbreviations

PEM	Proton exchange membrane
AC	Alternating current
DC	Direct current
η_{WT}	Wind turbine efficiency
A_{WT}	Wind turbine swept area
N_{WT}	Number of wind turbines
V	Wind speed
$V_{cut\text{-}in}$	Wind speed threshold for activation
$V_{cut\text{-}out}$	Wind speed threshold for deactivation

Responsible Editor: Mohamed Ksibi.

✉ Khaoula Adeli
k.adelieducation@gmail.com

[1] Hassan II Ain Chock University: Universite Hassan II Casablanca, Casablanca, Morocco

[2] Laboratory of Inorganic Materials for Sustainable Energy Technology (LIMSET), UM6P, Benguerir 43150, Morocco

[3] Laboratory of Engineering Sciences for Energy (LabSIPE), University Research Center (CUR) in Renewable Energies & Intelligent Systems National School of Applied Sciences, Chouaib Doukkali University, El Jadida, Morocco

Introduction

In the relentless pursuit of sustainable and renewable energy sources, unlocking the untapped potential of wind power has emerged as a beacon of promise. This quest has led to the exploration of integrating wind power into hydrogen production, particularly in coastal regions blessed with abundant winds. This paper presents a comprehensive technical analysis that delves into the harnessing of untapped wind power for sustainable hydrogen energy production in three Moroccan cities—Tetouan, Essaouira, and Tangier. This synergistic approach not only addresses the energy challenges of these coastal regions but also aligns with broader environmental preservation goals and the global transition towards carbon neutrality. Coastal regions, characterized by their consistent and high-speed winds, offer a unique opportunity for sustainable energy generation. Tetouan, Essaouira, and Tangier, situated along the Moroccan coastline, embody such regions with significant untapped wind potential. Building upon previous research on wind power in coastal areas, studies conducted globally, such as in the North Sea and the Mediterranean, have successfully demonstrated the viability of harnessing wind energy for electricity generation and other applications. A groundbreaking study by Onea et al. (2016) demonstrated the effective incorporation of wind power by assessing the wind potential in the proximity of the Mediterranean Sea to ascertain the feasibility of implementing offshore wind farms along coastal areas to provide a reliable source of electricity. This study serves as a guiding light for the exploration of untapped wind power in Moroccan coastal cities. The focus on hydrogen production in this analysis arises from its potential to reshape the energy landscape. Hydrogen, a versatile and clean energy carrier, can be stored and transported for various applications. By utilizing untapped wind power for hydrogen production, these coastal cities can establish a reliable and sustainable energy source while decoupling energy production from carbon-intensive processes. Recent advancements in hydrogen production, such as electrolysis powered by renewable energy (conducted by Adeli et al. 2024), have paved the way for green hydrogen production. Countries like Germany and Japan (Jensterle et al. 2019) have invested significantly in green hydrogen as part of their climate goals, offering a blueprint for the exploration in Tetouan, Essaouira, and Tangier. This technical analysis aims to evaluate the feasibility and potential benefits of integrating untapped wind power into hydrogen production in the Moroccan coastal cities. Specific objectives include assessing the wind resource potential, identifying optimal locations for wind farms, and analyzing the technical viability of coupling wind power with hydrogen production technologies. The exploration of untapped wind power for sustainable hydrogen energy production in Tetouan, Essaouira, and Tangier holds immense promise for addressing the energy needs of these coastal regions. By drawing inspiration from successful precedents and leveraging the latest advancements in wind power and hydrogen technologies, this analysis contributes valuable insights toward the development of a cleaner and more sustainable energy future for Morocco and beyond.

Green hydrogen production system

Study area description

This section offers a comprehensive view of our chosen study area and elucidates the reasoning behind the selection of specific Moroccan cities as the main subjects of our research. We have meticulously selected Tangier, Tetouan, and Essaouira, as shown in Fig. 1, due to their strategic importance in the arenas of renewable energy production

Fig. 1 Map of Morocco with an emphasis on the selected cities for study (Google Maps 2023)

and environmental sustainability, with a distinct emphasis on their potential for substantial hydrogen generation. Tangier, situated in the northern region of Morocco, has a prominent status as a crucial port city. Its geographical location along the Mediterranean coast presents unique wind patterns, making it a promising candidate for the utilisation of wind power in sustainable hydrogen production. Tetouan, located close proximity to Tangier, shares the advantage of coastal wind patterns and exhibits notable potential for the advancement of renewable energy initiatives. Its geographic location aligns seamlessly with our research objectives, further enriching the diversity of regions under our investigative lens. Essaouira, located on the Atlantic coast of Morocco, is well suited to receiving consistent and robust wind resources, designating it as another strategically significant city for our research. The prevailing wind patterns in Essaouira lay a robust foundation for our exploration into the feasibility of wind-powered hydrogen production. The spatial distribution of these selected cities is visually represented in Fig. 1, providing an essential geographical context for our study.

Through our focused examination of Tangier, Tetouan, and Essaouira, we endeavor to delve into the intricacies of wind patterns, the technical aspect of wind-to-hydrogen systems, and the overarching potential for harnessing wind energy to generate hydrogen. These cities, marked by their geographical diversity and strategic importance, play a pivotal role in our quest to unravel sustainable and environmentally friendly energy solutions within Moroccan urban landscapes.

Figure 2 describes our proposed setup, which integrates renewable energy generation with hydrogen production and storage, creating a sustainable energy system that efficiently uses wind power. We now present a comprehensive overview of this innovative system. At its core, a wind turbine harnesses the kinetic energy of the wind and converts it into mechanical power. This mechanical energy is then transformed into electrical energy through an attached generator. To make the electricity generated by the wind turbine suitable for hydrogen production, it must be converted from alternating current (AC) to direct current (DC). This conversion is achieved through an AC-to-DC conditioner or rectifier. The conditioner ensures a stable and consistent DC power supply for the subsequent hydrogen production process. Water plays a pivotal role in the hydrogen production process via electrolysis. A water tank is employed to store a supply of clean water, usually deionized or demineralized, which is essential for the electrolysis process. This stored water is fed into the electrolyzer, where it undergoes a chemical reaction to separate it into hydrogen and oxygen. The heart of the system is the proton exchange membrane (PEM) electrolyzer. This advanced device employs an electrolyte membrane to split water molecules into hydrogen and oxygen gas. The DC power from the conditioner is applied to the electrolyzer, driving the water-splitting process. Hydrogen gas is produced at the cathode, while oxygen gas is released at the anode. PEM technology stands out for its high efficiency and is particularly well suited for on-site hydrogen generation. The hydrogen gas produced by the electrolyzer is collected and safely stored in a hydrogen tank. These tanks are specifically designed to contain and store hydrogen gas until it is required for various applications. The stored hydrogen can be utilized as a clean fuel source for hydrogen fuel cells, for various industrial processes, or for other applications. In summary, this integrated system combines

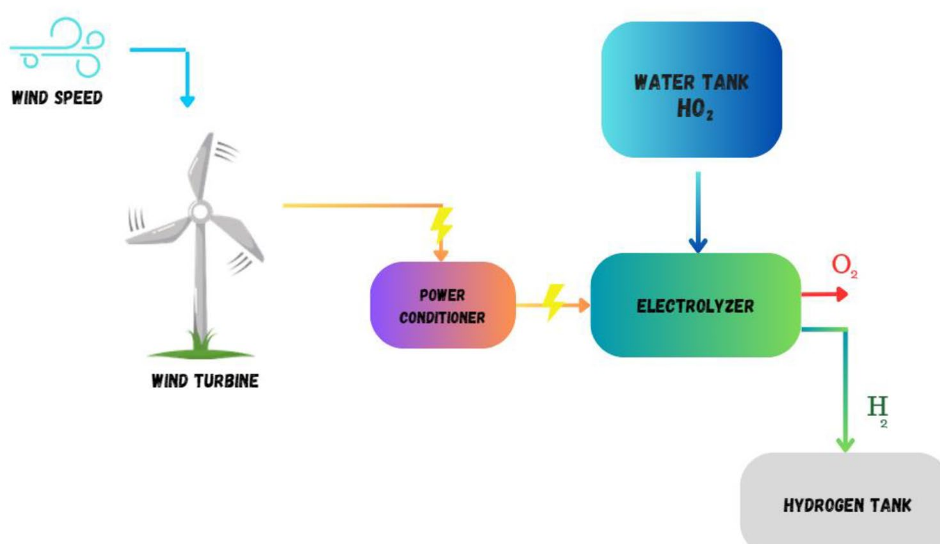

Fig. 2 Scheme of green hydrogen production using wind-based renewable resources (Engel 2021)

the advantages of renewable wind energy generation with hydrogen production and storage. It offers a clean and sustainable approach to electricity generation and hydrogen production for diverse applications.

A mathematical modeling approach

In this intriguing segment, we discuss the foundational mathematics that dictate the effectiveness, dependability, and overall functionality of our eco-friendly hydrogen production system. Through the creation of a mathematical framework, our goal is to unravel the intricate relationships between renewable energy sources and hydrogen production methods.

Table 1 Characteristics of an Eno 114 wind turbine (Eno Energy Systems 2024)

Symbol	Description	Value	Unit
P_{rated}	Rated power of turbine	4000	kW
$V_{cut\text{-}in}$	Cut-in speed	3	m/s
$V_{cut\text{-}out}$	Cut-out speed	25	m/s
V_{rated}	Rated speed	13.5	m/s
A_{wT}	Swept area	10,369	m^2

- Model wind turbine

In our existing hybrid system, we make use of seven Eno 114 horizontal-axis wind turbines (Eno Energy

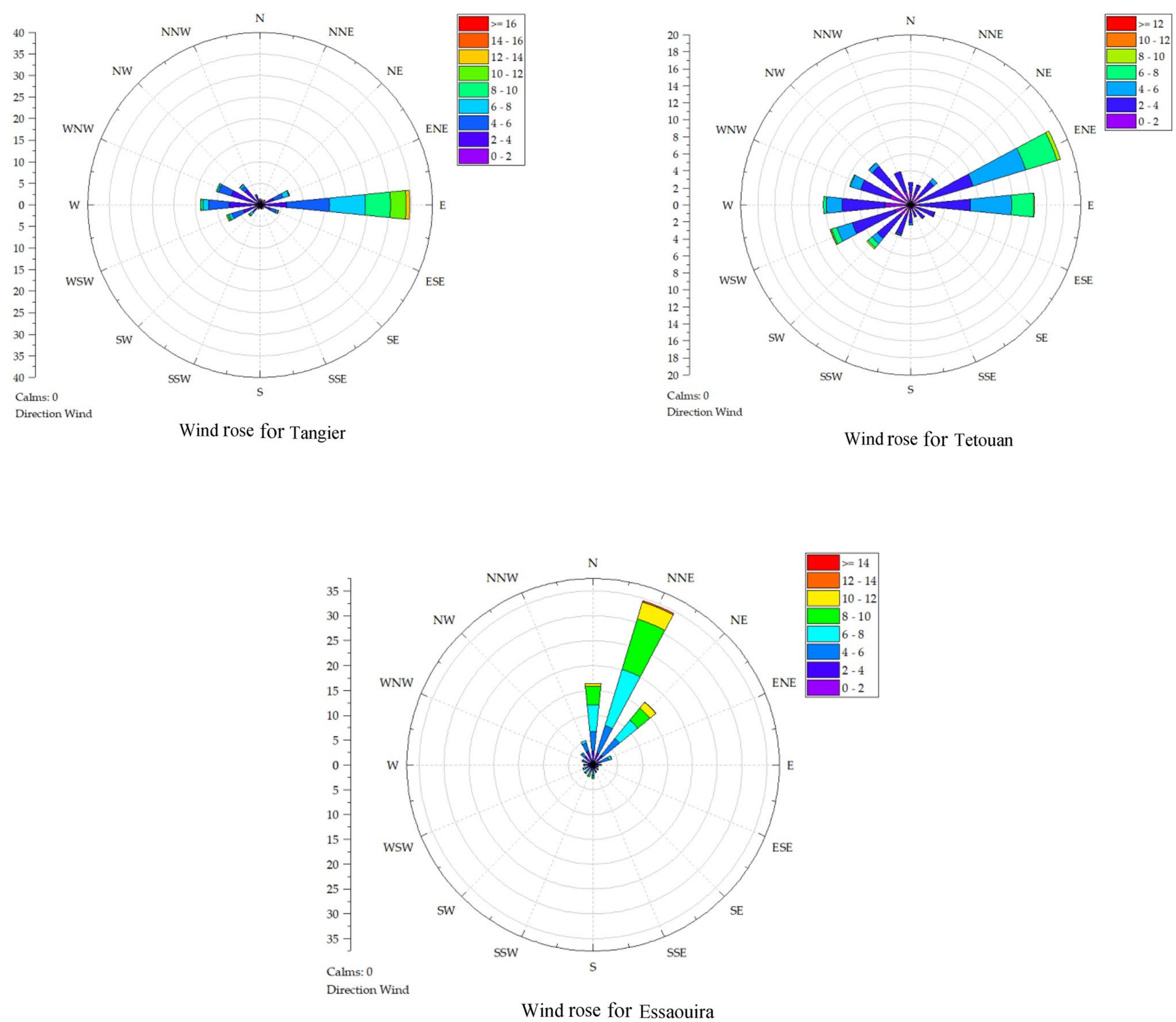

Fig. 3 Wind roses of the wind speeds at three cities (Tangier, Tetouan, and Essaouira)

Systems 2024), as illustrated in Fig. 3 and outlined in Table 1. These wind turbines play a crucial function in converting the kinetic energy of the wind into electrical power. To estimate the electrical power produced by these turbines, we can apply the following fundamental equations (we suppose that the wind efficiency equals 92%):

$$P_{\mathrm{WT}} = 0 \rightarrow \text{for } V < V_{\text{cut-in}} \text{ and } V > V_{\text{cut-out}} \tag{1}$$

$$P_{\mathrm{WT}} = P_{\text{rated}} \times \eta_{\mathrm{WT}} \rightarrow \text{for } V_{\text{rated}} < V \leq V_{\text{cut-out}} \tag{2}$$

$$P_{\mathrm{WT}} = \left(P_{\text{rated}} \times \frac{V^3 - V^3_{\text{cut - in}}}{V^3_{\text{Rated}} - V^3_{\text{cut - in}}} \right) \times \eta_{\mathrm{WT}} \rightarrow \text{for } V_{\text{cut - in}} < V \leq V_{\text{rated}}. \tag{3}$$

In our current hybrid setup, the Eno 114 wind turbines are engineered for the conversion of wind kinetic energy into electrical power. This conversion process is made possible by the turbine's rated power (P_{rated}), denoting its maximum electrical output capacity. The turbine initiates power generation once the wind speed exceeds the cut-in speed ($V_{\text{cut-in}}$) and ceases operation to protect against damage when the wind speed exceeds the cut-out speed ($V_{\text{cut-out}}$). At the rated speed (V_{rated}), the turbine achieves its peak efficiency, ensuring optimal energy transformation. The efficiency (η_{WT}) further guarantees that a significant proportion of the kinetic energy is efficiently converted into electrical power. The key variables at play in this process include η_{WT}, A_{WT}, N_{WT}, P_{rated} in kW, V in m/s, $V_{\text{cut-in}}$ and $V_{\text{cut- out}}$.

Within the current system, the Eno 114 horizontal axis wind turbines possess the capacity to produce electrical power of up to 4000 kW.

- Model power conditioner

Within this hybrid system, the pivotal role of orchestrating the integration of diverse energy sources falls to the power conditioner unit. The need for such a unit arises because wind turbines generate alternating current (AC), whereas most devices require direct current (DC) to operate effectively. To surmount this challenge, the system incorporates a power conditioner comprising two essential power converters: one exclusively dedicated to the conversion of AC to DC (AC/DC) and the other meticulously designed for the conversion of DC to DC (DC/DC). This configuration is visually represented in Fig. 1. In this context, the electrical power produced by the wind turbine is guided through an AC/DC rectifier, establishing a connection to the DC bus. These converters are interconnected via the DC bus, which delivers the required current to the electrolyzer. Additionally, the power conditioner unit performs the indispensable role of supplying the essential power to the compressor. It is noteworthy that the efficiency of all these converters consistently maintains a presumed and constant level of 95% (Nasser et al. 2022). The fundamental principle governing the power conditioner model can be succinctly encapsulated by the following equation:

$$P_{\mathrm{EZ}} = \left[P_{\mathrm{WT}} \times \eta_{\frac{\mathrm{AC}}{\mathrm{DC}}} \right]. \tag{4}$$

- Electrolyzer model (PEM)

The generation of hydrogen using electricity from wind power systems relies on the process of water electrolysis. This involves the integration of renewable energy systems with an electrolyzer. The appeal of this combination lies in the fact that wind technologies inherently provide the necessary DC for the electrolyzer to operate, eliminating the need for an AC/DC converter. Although various electrolyzer technologies are available, PEM and alkaline electrolyzers are the most well established and commonly utilized in commercial applications. For the purposes of this study, we have chosen PEM technology to drive the water electrolysis process. In PEM electrolyzers, an acidic polymer membrane acts as the electrolyte, in which hydrogen is separated from oxygen in water under the influence of an electric current. This process involves the use of a negatively charged cathode and a positively charged anode. Additionally, PEM electrolyzers offer extended operational lifetimes, high efficiency, a wide operational range, and rapid dynamic response times. These attributes make them well suited to accommodating fluctuations in electricity production, a common occurrence with intermittent renewable energy sources like wind technologies. It is important to emphasize that producing 1 kg of hydrogen through electrolysis requires 52.5 kWh of energy, with an associated efficiency rate of 75%. This efficiency encompasses all the energy requirements of the electrolysis process, including energy losses, the electrolysis cell stack, and any additional energy demands as outlined in the literature (Touili et al. 2022).

$$m = \frac{P_{\mathrm{EZ}} \times \eta}{\mathrm{HHV}_{\mathrm{H2}}}. \tag{5}$$

Within this framework, the variable m represents the amount of hydrogen produced, expressed in kilograms. P_{EZ} signifies the quantity of electricity generated, measured in kilowatt hours (kWh). $\mathrm{HHV}_{\mathrm{H2}}$ is an abbreviation for the higher heating value of hydrogen, set at 39.4 kWh per kilogram. Lastly, η denotes the efficiency of the electrolyzer, which is assumed to be 75%.

Computational simulation and validation

We present the results of our simulation of the climatic conditions in four distinct Moroccan cities with the aim of generating compressed hydrogen using wind turbines. These outcomes are displayed on an hourly basis and cover the span of 1 year. The data collection process for our study was carefully designed to establish a strong foundation for analyzing crucial parameters; specifically, the total wind speed, as depicted in Fig. 3 and Table 2. These parameters play a vital role in assessing the wind energy potential in the selected regions. Our data-gathering approach was methodical and relied on reputable sources, including NASA's Prediction of Worldwide Energy Resources (POWER; POWER Project Team 2023), known for its reliability and precision in providing precise monthly wind-speed data. This comprehensive approach spanned an entire year, totaling 8760 h. This long duration allowed us to delve deep into the examination of seasonal variations and long-term trends in wind speed. The result of this meticulous data collection and analysis ensures the reliability and significance of our findings. By amalgamating data from these respected sources and adopting an extended time frame, our research is fortified with a robust and comprehensive dataset. This, in turn, enables a thorough assessment of the wind energy potential in the chosen regions. Figure 3 illustrates the prevailing wind directions in Essaouira, Tetouan, and Tangier, with the north–north–east, east–northeast, and east sectors being predominant in the three cities, accounting for 67%, 36%, and 46% of the wind, respectively. South winds are rare across all locations. Examining wind speed variations along these three directions, the longest spokes, provides valuable insights:

- Tangier: winds ranging from 2 to 4 m/s occur 6.5% of the time, followed by 4–6 m/s (10%), and 6–8 m/s (10%). Higher speeds become progressively less frequent.
- Tetouan: similar to Tangier, wind speeds gradually increase in frequency, with 2–4 m/s occurring 7% of the time and 4–6 m/s occurring 6% of the time.
- Essaouira: the occurrence rate of 4–6 m/s is 8%, that of 6–8 m/s is 12%, and that of 8–10 m/s is 10.5%. Higher speeds are even less common than in Tangier and Tetouan.

Table 2 Location data (POWER Project Team 2023)

Description	Tangier	Tetouan	Essaouira
Latitude	35.7789	35.5831	31.512
Longitude	− 5.8048	− 5.3622	− 9.7612
Geographical region in deg. latitude and longitude	50.61 m	218.16 m	72.73 m
Dates (month/day/year)	01/01/2022–12/31/2022	01/01/2022–12/31/2022	01/01/2022–12/31/2022

This analysis underscores the significant potential for renewable energy production in these regions, as the consistent speeds offer a reliable and promising resource.

- Monthly power and hydrogen output production

In Fig. 4, along with Table 3, we provide an extensive examination of the seasonal patterns of power generation from diverse renewable energy sources in three significant Moroccan urban centers: Tangier, Tetouan and Essaouira. These visual representations grant us valuable insights into the fluctuations and long-term trends in the production of wind energy throughout the year. Figure 4 offers a visual depiction of the data, while Table 3 delivers a comprehensive overview of the main discoveries. We now explore the observations and the significance of these vital datasets.

Within the context of the energy and resource dynamics in three Moroccan cities, namely Tangier, Tetouan, and Essaouira, the table offers a thorough summary of both the overall power generation and the production of hydrogen. Tangier boasts a substantial wind power output of 9.96 GW throughout the year, which is derived from wind turbines, and utilizes this renewable energy source to produce 180.41 tonnes of hydrogen (Table 4). In Tetouan, a commendable 2.93 GW of wind power is generated annually, contributing to the region's renewable energy production and resulting in the production of 53 tonnes of hydrogen. Essaouira is a standout in wind energy production, with a remarkable yearly output of 19.78 GW. This clean and sustainable energy source is harnessed to produce a substantial 358 tonnes of hydrogen, making a significant contribution to the region's energy landscape.

Conclusion

In conclusion, our in-depth exploration of the integration of untapped wind power into hydrogen production in Moroccan coastal cities has unveiled a promising trajectory toward sustainable energy solutions. Through meticulous analysis of seasonal power-generation patterns that emphasizes wind energy sources and by providing a comprehensive overview of the total power output and hydrogen production, this research underscores the pivotal role of renewable energy in shaping Morocco's energy landscape. The findings highlight the dynamic nature of wind power output, showcasing the adaptability of coastal regions to harness

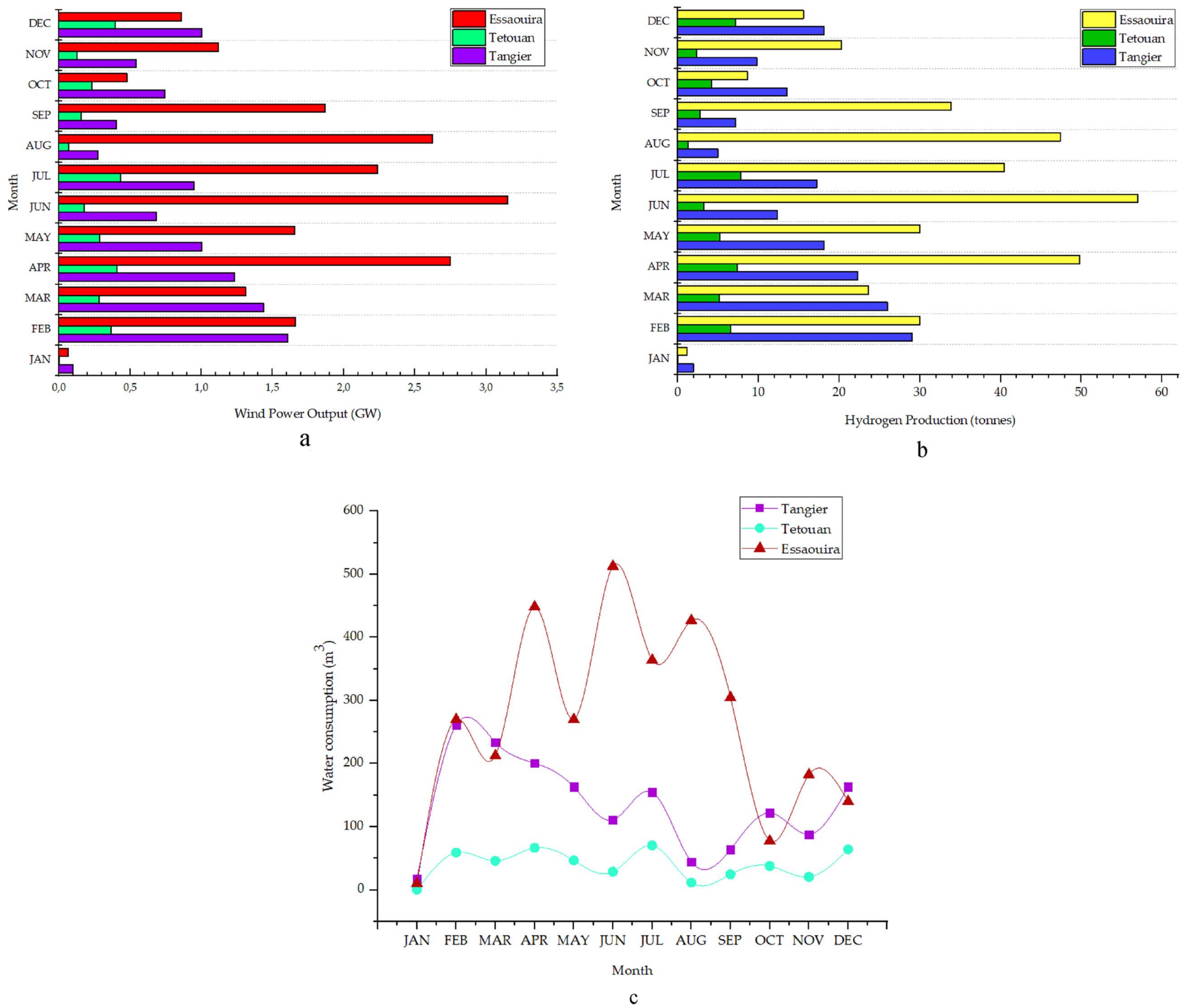

Fig. 4 Seasonal power and hydrogen generation. **a** Wind power output per month in three cities (Tangier, Tetouan, Essaouira). **b** Hydrogen output per month in three cities (Tangier, Tetouan, Essaouira). **c** Water consumption (in hydrogen production units per month) in three cities(Tangier, Tetouan, Essaouira)

abundant wind resources for hydrogen production. Notably, Essaouira emerges as a leader in both wind power generation and hydrogen production, making significant contributions to the region's renewable energy portfolio. The analysis of the data collected hourly for a year offers not only valuable insights into the fluctuations and trends in wind energy production but also a robust foundation for informed decision-making and policy development. The research, characterized by meticulous data collection from reliable sources and an extended time frame for analysis, ensures the reliability and relevance of the findings. Furthermore, this research acts as a valuable resource for stakeholders, equipping them with essential information for a detailed evaluation of wind energy potential in the selected regions. We conclude that this study significantly contributes to our understanding of renewable energy dynamics in Moroccan cities, with a specific emphasis on the importance of wind power. It serves as a cornerstone for informed energy planning and policy development, with the potential to drive the adoption of sustainable and environmentally friendly energy practices in the future. The insights garnered not only benefit Morocco but also contribute to the broader global effort towards a cleaner and more sustainable energy future. Additionally, the pivotal importance of hydrogen production in Morocco's

Table 3 Seasonal energy production summary

Wind power output	The monthly power production, measured in gigawatts (GW), exhibits dynamic patterns throughout the year. In January, the total power generated is 0.0977 GW, with secondary values of 0.00252 GW and 0.062 GW. February sees a significant increase to 1.60 GW, accompanied by secondary values of 0.36 GW and 1.65 GW. March maintains high levels, with 1.43 GW, 0.28 GW, and 1.30 GW for the total and secondary values, respectively. April marks a peak in total power at 1.23361 GW, driven by secondary values of 0.40 GW and 2.75 GW. The subsequent months display fluctuations, with June experiencing a notable drop in total power to 0.68 GW, with secondary values of 0.17 GW and 3.15 GW. July and August show varying levels of total power and secondary values. The rest of the months continue to demonstrate shifts in power production, with December ending the year at 1.00 GW, with secondary values of 0.39467 GW and 0.861 GW. Overall, the data highlight the changing dynamics of power generation, emphasizing the influence of secondary factors on the total power output each month
Hydrogen production	The monthly hydrogen (H_2) production, measured in tonnes, varies across the cities of Tangier, Tetouan, and Essaouira. In January, Tangier leads with 1.91 tonnes, followed by Essaouira at 1.13 tonnes and Tetouan with 0.04931 tonnes. February sees a significant increase in production, particularly in Tangier, with 29 tonnes, followed by Tetouan at 6.57 tonnes and Essaouira at 29.99 tonnes. Throughout the subsequent months, each city experiences fluctuations in hydrogen production. April witnesses a notable peak in Essaouira at 49.83 tonnes, while Tangier and Tetouan produce 22.30 and 7.39 tonnes, respectively. The summer months show a decrease in overall production, with June indicating a spike in Essaouira at 56.97 tonnes. The remaining months continue to demonstrate dynamic patterns in hydrogen production for the three cities, reflecting regional variations in this essential industrial process

Table 4 System production analysis

Description	Tangier	Tetouan	Essaouira
Total wind power output in GW over the year (PWT)	9.96	2.93	19.78
Total hydrogen production output in tonnes over the year	180.41	53	358

pursuit of a sustainable and resilient energy future cannot be overstated. As a nation committed to harnessing renewable energy, Morocco sees hydrogen production as a key enabler for storing and utilizing surplus clean energy. This initiative aligns seamlessly with global efforts to transition towards green hydrogen derived from renewable sources as a clean alternative to conventional fossil-fuel-based hydrogen. The integration of hydrogen production plays a crucial role in diversifying Morocco's energy mix, reducing its dependence on fossil fuels and bolstering the nation's resilience to energy market fluctuations. Moreover, it contributes significantly to the overarching goal of decarbonizing the energy sector, thereby mitigating the environmental impact and addressing climate change concerns. Beyond environmental benefits, hydrogen production in Morocco holds economic promise by creating new job opportunities in the renewable energy and hydrogen technology sectors. It also positions the country on the global stage as a potential player in the emerging hydrogen economy, fostering international collaborations and technological advancements. In essence, the importance of hydrogen production in Morocco extends beyond immediate energy needs. It serves as a catalyst for sustainable development, economic growth, and global participation in shaping a cleaner and more resilient energy landscape.

Declarations

Conflict of interest The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

Adeli K, Nachtane M, Faik A, Rachid A, Tarfaoui M, Saifaoui D (2024) A deep learning-enhanced framework for sustainable hydrogen production from solar and wind energy in the Moroccan Sahara: Coastal regions focus. Energy Convers Manag 302:118084. https://doi.org/10.1016/j.enconman.2024.118084

Engel J (2021) Europe's offshore wind to green hydrogen plan won't work for the US, report finds, https://www.renewableenergyworld.com/wind-power/europes-offshore-wind-to-green-hydrogen-plan-wont-work-for-the-us-report-finds/#gref. Accessed 4 Nov 2023

Eno Energy Systems (2024) Eno 114 4.0 MW turbine. Technical data. Eno Energy Systems, Rostock

Google Maps (2023) Morocco. https://www.google.com/maps/place/Maroc/@31.7006983-2.4429037,6z/data=!3m1!4b1!4m6!3m5!1s0xd0b88619651c58d:0xd9d39381c42cffc3!8m2!3d31.791702!4d-7.09262!16zL20vMDR3Z2g?entry=ttu. Accessed 4 Nov 2023

Jensterle M, Narita J, Piria R, Samadi S, Prantner M, Crone K et al (2019) The role of clean hydrogen in the future energy systems of Japan and Germany. Adelphi Consult GmbH, Berlin

Nasser M, Megahed TF, Ookawara S, Hassan H (2022) Techno-economic assessment of clean hydrogen production and storage using hybrid renewable energy system of PV/wind under different climatic conditions. Sustain Energy Technol Assess 52:102195. https://doi.org/10.1016/j.seta.2022.102195

Onea F, Deleanu L, Rusu L, Georgescu C (2016) Evaluation of the wind energy potential along the Mediterranean Sea coasts. Energy Explor Exploit 34:766–792. https://doi.org/10.1177/0144598716659592

POWER Project Team (2023) POWER Data Access Viewer. https://power.larc.nasa.gov/data-access-viewer/. Accessed 20 Oct 2023

Touili S, Bouaichi A, Alami Merrouni A, Illah AA, El Amrani A, El Hassouani Y et al (2022) Performance analysis and economic competiveness of 3 different PV technologies for hydrogen production under the impact of arid climatic conditions of Morocco. Int J Hydrogen Energy 47:31596–31613. https://doi.org/10.1016/j.ijhydene.2022.07.088