Journal of Harbin Engineering University
ISSN: 1006-7043

Vol 44 No. 12
December 2023

Assessment of Wind-to-Hydrogen Production via Electrolysis: A Case Study in Morocco

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Abstract

In response to green hydrogen roadmap where Morocco expects a demand of 14 TWh by 2030, the present work studies the potential of green hydrogen production in the windiest sites via electrolysis. Nine sites belonging to the windiest areas of Morocco were selected, where the average wind speed exceeds 6 m/s. The purpose is to identify the best site that will allow to met the hydrogen demand with a competitive levelized cost of hydrogen (LCOH). To accomplish this, the methodology adopted considers first a diagnosis of the operational onshore wind farms. Then, with the help of the Weibull distribution generated from WindPro software and using mathematical models, the best site for hydrogen production was identified as the exemplary site and energy savings were calculated referring to this site. Finally, the economic study was carried out to determine the levelized cost of energy (LCOE) as well as the LCOH. The results demonstrated that the site of Tetouan provides a high wind potential with a significant capacity factor of 55%.The required capacity to install in order to reach the hydrogen demand is about 7 GW. The economic evaluation revealed a LCOE up to 0.029 $/kWh and the LCOH reaches 1.86 $/kgH$_2$.

Keywords:electrolysis, green hydrogen, LCOE, LCOH, onshore wind farm.

1. Introduction

The power generation of renewable energy, for instance, is the main energy source of future energy strategy. However, the intermittence and instability of renewable energy have brought major challenges to the stable operation of the power system, opening temporal and spatial gaps between the consumption of the energy by end-users and its availability. Due to this intermittency, energy storage has an essential role to play in the energy transition. Hydrogen technology, with its many advances, has been recognized as the most promising choice [1]. Green hydrogen is an identified efficient energy carrier as part of a decarbonisation process to reduce carbon emissions. It presents a strong potential that can be used in several sectors: industry (chemicals, steel production, etc.), transport (fuel), building (heating) and the energy sector (fuel cells), since it is safely produced from clean green energy, including solar, wind, biomass, and geothermal energy; environmentally friendly approach [2–5].

In the long term, hydrogen can complement renewable electricity and be the keystone of a 100% renewable future [6]. It is worth noting that conventional energies are beneficial, however, they release a lot of carbon dioxide into the environment during combustion [3]. In this context, researchers' interest in exploring techniques of creating hydrogen from green energies has grown in recent years[7–9]. Among the existing processes for producing green hydrogen, electrolysis and biomass gasification are the most established on a large scale [10].

Nevertheless, electrolysis remains the most common process for producing green hydrogen, accounting for 4% of total hydrogen production worldwide [11–13]. To date, it is the only technology on the market that can compete in terms of maturity with steam methane reforming (SMR), given that it is the least hazardous and most environmentally friendly technology and it has reached a technology readiness level (TRL) of 7-8 (system demonstration/development) and a commercial readiness index (CRI) of 4-5 (deployment)[14,15].

According to [16], although biomass-based hydrogen production technology meets green hydrogen standards, it still needs to be improved in line with current calculations of the carbon footprint of the hydrogen production process, in order to achieve carbon-free energy consumption. In this regard, we also cite the study conducted by [17], whose results showed that the electrolysis process is strongly recommended over other processes (biological and thermochemical). These results were established based on a comparison of 10 green hydrogen production processes using both the analytic hierarchy process (AHP) and Fuzzy Vikor weighting and prioritization methods. Nevertheless, electrolysis is highly sensitive to electricity supply. Water supply and the use of rare materials in some electrolysis technologies must be overcome to fully justify this green hydrogen infrastructure [18].

However, these issues are no longer considered as big issues for this technique, since its improvement has aroused the interest of many authors. Several scenarios have been proposed, including but not limited to the following: Electrolysis of recovered wastewater from the textile industry [19], the use of demineralized salt water [20], reducing the dependence on noble materials (Pt, Pd, Au, Ag, Ru and Ir) ,etc [21]. As a result, we can clearly discern that combining water electrolysis with wind, solar and other renewable energies is the main route to eliminating the carbon footprint: Zero emissions.

Fig.1 represents green hydrogen value chain. As it is shown, hydrogen energy can be used in various forms, including a fuel cell after storage, which can achieve high-energy conversion efficiency [22,23]. Currently, the generation of green hydrogen from wind electricity via electrolysis is gaining attraction due to its simplicity, lowest greenhouse gas emissions (GHG) among all hydrogen generation resources, and lowest cost [24].

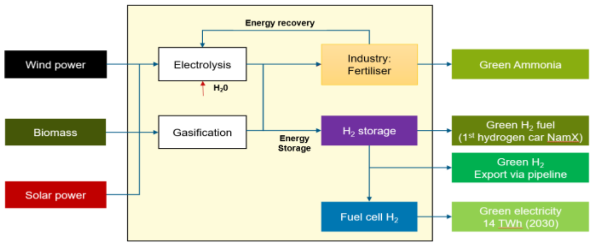

Fig. 1. Schematic diagram for hydrogen value chain.

Morocco's energy supply is still mostly based on fossil fuels, with a total energy supply (TES) of 880 PJ in 2020 (Fig.2). The TES distribution in 2020 was as follows: oil constituted 55%, coal accounted for 32%, biofuels and waste made up 6%, wind and solar represented 4%, natural gas contributed 3%, and hydro had a share of 0.4%. By 2020, according to Fig.3, the part of renewables in the TES approached 10%. Nevertheless, Morocco's total final energy consumption in 2020 was 653 PJ, accounting for 74% of total primary energy supply (see Fig.4). Transportation holds the highest share, accounting for 35% of total final energy consumption, with the residential sector coming in second at 27%. The rapid rise of Morocco's population is expected to result in a significant increase in the country's energy usage. In recent decades, Morocco has largely relied on energy imports. Morocco's net energy imports reached 871 PJ in 2021[25].

In response to this situation, the government has been compelled to pursue a several strategies, programs and projects aimed at reducing its energy dependency, increasing energy security, and mitigating the effects of climate change, since it presents a good potential to become a net-zero emissions country in the short term, due to the sufficient availability of renewable energy sources [26,27], especially solar and wind energy [28].

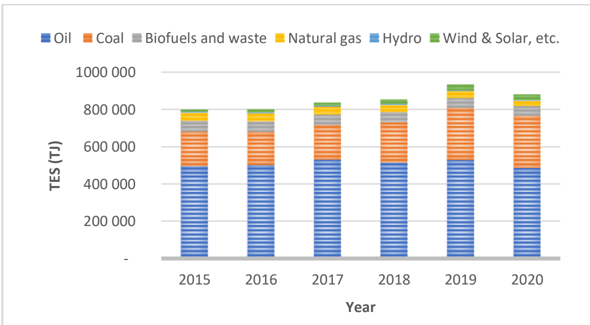

Fig. 2. Total energy supply (TES) by source, Morocco 2015-2020[29].

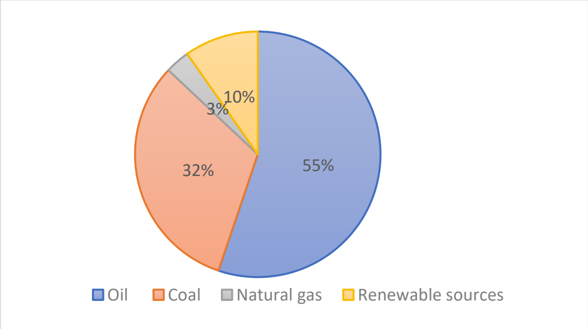

Fig. 3. Percentage of the energy supply from renewable energy sources (%).

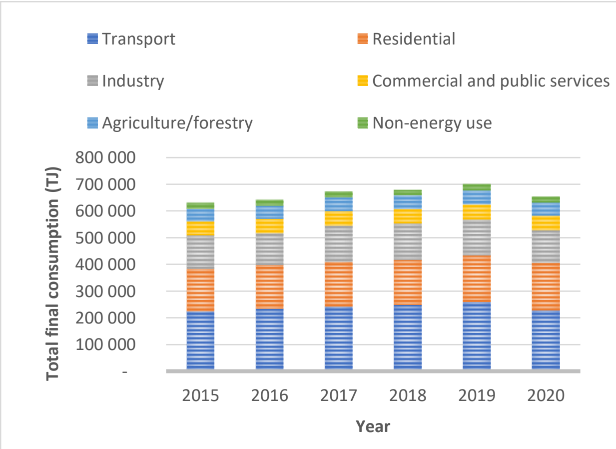

Fig. 4. Total final consumption in Morocco, by sector, 2015- 2020[27].

In this context, it should be noted that the technical potential for photovoltaic and onshore wind power is about 49 000 and 11 500 TWh respectively [30]. These energy sources are the most widely used for electricity generation in Morocco.

Wind energy presents a significant trend at the national level both in terms of electricity production in a centralized manner and for industrial and urban needs. According to the national energy strategy, the wind power program aims to increase installed wind power capacity to 2 GW by the end of 2020 and to 4.2 GW by 2030 [31,32]. Renewable energy statistics report established by the International Renewable Energy Agency (IRENA), shows that Morocco has reached an installed capacity of 1.43 GW in 2021, a significant evolution compared to previous years [33]. In 2022, the installed capacity represents 1.81 GW distributed over 9 sites (Tetouan, Tangier, Taza, Midelt, Essaouira, Tarfaya, Laâyoune, Boujdour, Safi) belonging to the windiest areas (Z5, Z6, Z7) of Morocco where the average wind speed exceeds 6 m/s according to Table 1. Fig.5 shows the three major areas where the potential for wind power generation is significant: the Strait of Gibraltar, the Atlantic coast between the south of El Jadida and the north of Agadir, almost the entire coast of the Saharan provinces, as well as some sites of the “Taza corridor”[34] are mentioned. A classification of the average wind speed in 3 categories (low, medium and high) defined by the International Electrotechnical Commission (IEC) standard, as shown in Table 2, shows a predominance of low to medium wind for the 9 sites (Fig.6), with an average wind speed ranging between 7 and 10.5 m/s.

The presented sites provide an approximate production of 6622 GWh and consequently an emission mitigation of about 4.9 million teqCO_2 [35,36]. On the other hand, Fig. 7-8-9 represent respectively the evolution of installed farms, energy production in the national territory over time as well as the distribution of installed capacity between the different sites.

Table 1. Classification of wind zones in Morocco.

Zone	Sites	Speed class
Z1	Marrakech - Meknès- Fès	< 3m/s
Z2	Rabat-Kenitra- Casablanca-Nador-Oujda-Er-Rachidia-Tata	3-4 m/s
Z3	Agadir	4-5 m/s
Z4	-	5-6 m/s
Z5	El Jadida-Safi	6-7 m/s
Z6	Midelt-Taza- Tantan-Tarfaya-Laayoune	7-8 m/s
Z7	Dakhla-Boujdour - Essaouira-Tanger-Tetouan	>8 m/s

Table 2. Specifications of wind classes [37].

Wind class	Annual average speed (m/s)
High wind: IEC I	10
Medium wind: IEC II	8.5
Low wind: IEC III	7.5

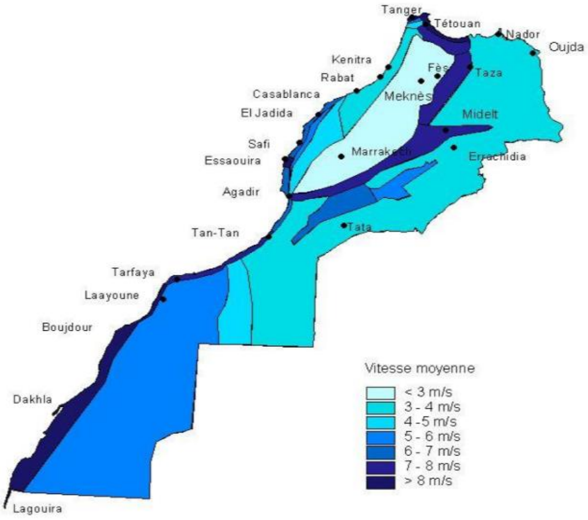

Fig. 5. Morocco wind map[34].

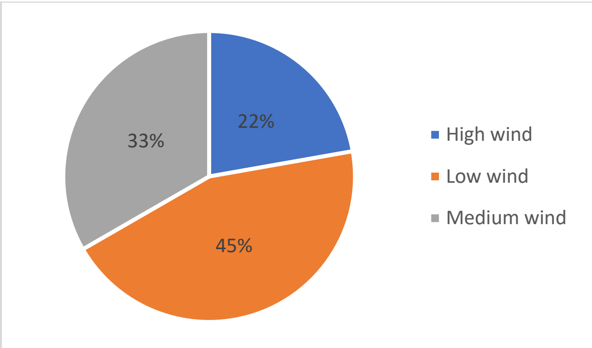

Fig. 2. Distribution of wind classes for the sites under study.

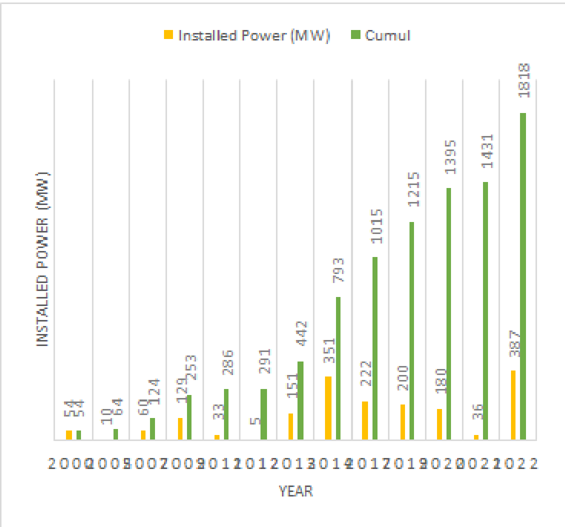

Fig. 7. Evolution of installed wind farms over time and in the national territory.

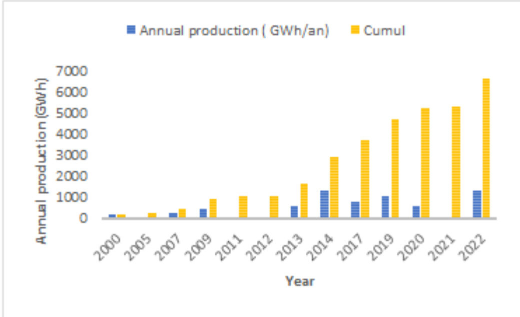

Fig. 8. Evolution of energy production of installed wind farms.

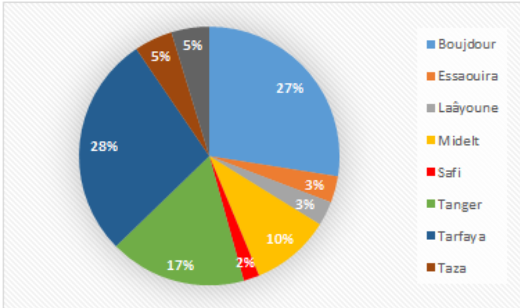

Fig. 9. Distribution of installed capacity among existing sites.

In response to the national energy strategy that sets a target of integrating renewable energy into the energy mix at a rate of 52% by 2030 and the Nationally Determined Contributions (NDC) Morocco, which aims to achieve GHG emissions reduction of 45.5%, several incitements are presented to reach a successful energy transition. In this context, a green hydrogen roadmap has been established under the National Hydrogen Commission (created in 2019), where Morocco expects a demand of up to 14 TWh by 2030: 4 TWh for local hydrogen market and 10 TWh the export market [38].

Moreover, Morocco has envisaged the implementation of two projects within the framework of the Germany-Morocco partnership (2020). The first project (Power-to-X) focuses on various energy production techniques, in particular green hydrogen, planned by the Moroccan Agency for Sustainable Energy (MASEN). It aims to minimize 100 000 tonnes of CO_2 emissions and develop the first green hydrogen plant in Africa, including the construction of a hybrid photovoltaic/wind plant with an electrolysis capacity of 100 MW to meet the demand of the green hydrogen plant. The second project involves setting up a Power-to-X research platform in cooperation with the Moroccan Research Institute for Solar Energy and

New Energies (IRESEN) [39]. In addition, the Office Chérifien des Phosphates (OCP) has agreed with Shell Energy to set up a 9 MWh pilot plant for green hydrogen and ammonia, with the aim of replacing 2 Mt/year of imported grey ammonia by green ammonia. Furthermore, another green H_2 and NH_3 plant is being prepared for feasibility by Total-Eren (France) in Guelmim-Oued Nour [40].

To date, the production of green hydrogen is relatively expensive compared with traditional production processes. According to the European Commission's Hydrogen 2020 strategy, green hydrogen costs around 3$/kg to 6.55$/kg[41]. Fossil hydrogen on the other hand costs around 1.80$/kg. In order for hydrogen to become a viable alternative to conventional fuels, several measures should be taken to keep the cost of hydrogen within the range of 1$ to 1.5$/kg of hydrogen, in order to compete with other fossil fuel-based energy sources [42]. It has been estimated that the production cost of green hydrogen will have to drop by more than 50% to 2.0$ to 2.5$/kg by 2030. It could also approach 0.65/kgH_2$ for the most optimal scenarios, while it could cost 1.25/kgH_2$ for the most pessimistic scenarios by 2050 [43]. In this regard, several technico-economic studies have been carried out at both national and international level, with a view to determining the levelized cost of hydrogen (LCOH).

At the national level, [44] conducted a technico-economic study for green hydrogen production from wind turbine and PV panel's combination. The most significant LCOH was about 2.54 $/kg for Dakhla city. Besides, [45] established an analysis of green hydrogen production by water electrolysis from different solar energy systems (fixed PV, 1-axis PV, 2-axis PV, stirling dish) and under different climatic conditions in Morocco. It was concluded that the 1-axis PV system enabled low-cost hydrogen generation, with a LCOH of 5.57$/kg. Moreover, an assessment of green hydrogen production from solar energy was carried out by [46]. The results showed that Morocco has a significant potential for hydrogen production from solar energy, with hydrogen production reaching around 3.3 x 10^9 tonnes/year from a solar potential of between 340 and 437 GWh/km^2, with hydrogen production costs ranging from 4.64 to 5.79$/kg. Another study established by [47], which consists in the technico-economic evaluation of the potential of wind energy and the production of green hydrogen in Casablanca, revealed an LCOH of 13.52 $/kWh. [48] conducted a technico-economic assessment of green hydrogen production from renewable sources: wind and solar in 3 high-potential cities: Laayoun, Ouarzazate, Midelt. The results showed that in Laayoune, the production of hydrogen from a wind system is the optimal configuration compared with solar and hybrid, both in terms of the quantity of hydrogen produced, which exceeds 51 tons/year for a wind capacity of 1 MW, and in terms of the LCOH, which is estimated at 1.72 $/kg. This is due to the high wind potential in Laayoune, which leads to a lower electricity cost. However, Ouarzazate and Midelt are the favorable sites for hydrogen production from solar energy, with LCOH of 2.32 and 2.42 $/kg respectively. Furthermore, a recent study focused on exploring the potential for green hydrogen production in distinct geographical locations in the Middle East and North Africa (MENA): Egypt, Morocco and the Gulf region, taking advantage of solar and wind energy. In Morocco, the results of the study revealed that hydrogen production costs in Tangier, Jorf Lasfar and Tantan are in the order of 9.2$, 13$ and 8/kgH_2$ respectively [27].

On an international scale, recent studies established in the Sultanate of Oman and the republic of Djibouti revealed a LCOH from wind energy ranging from 3.37–6.13 $/kg and 1.79- 3.38 $/kg, respectively in the windiest sites [49,50]. Whereas, [51] reveal a very competitive levelized cost of hydrogen reaching 1.214 $/kg$H_2$ using wind energy in Algeria. Besides, [52] carried out a techno-economic analysis of green hydrogen production by electrolysis using wind power at four sites in Saudi Arabia. It was found that the LCOH generated on the four sites considered ranged from 2.82/$kg in Dhahran to 3.81$/kg in Rafha. In Egypt, two studies have been carried out by [53] and [54] to assess green hydrogen production according to several configurations: use of wind energy, use of solar energy, hybridization (PV+Wind). The results showed that wind power is the most profitable scenario in terms of net present value (NPV), operating cost and lowest LCOH, with no CO_2 emissions. The LCOH ranges between 3.73$/kg and 4.13$/kg. Furthermore, a techno-economic study of a decentralized production of green hydrogen via solar-powered electrolysis has been carried out. Six scenarios were established, differing according to electrolyser type and grid connection. The results of the study showed that hydrogen produced using on-grid solar photovoltaic systems coupled with alkaline electrolyzers is the cheapest, with an LCOH of 6.23 EUR/kg [55].

Regarding the potential and the importance of wind power generation and hydrogen production for Morocco's future development and after carefully reviewing the literature, it can be seen that the LCOH from renewable energy remains high in Morocco and no studies have been conducted on comparison of the existing operational wind farm potential for green hydrogen production. In this regard, the authors of this paper conducted a technico-economic assessment on wind energy and hydrogen production potential in the 9 sites (Tetouan, Tangier, Taza, Midelt, Essaouira, Tarfaya, Laâyoune, Boujdour, Safi). The purpose is to identify the best site that will allow to met the hydrogen demand (14 TWh) with the lowest LCOH. These sites belong to the windiest areas (Z5, Z6, and Z7) of Morocco, where the average wind speed exceeds 6 m/s and the wind farms have already been installed. Among these sites, the best site is determined on the basis of wind mapping and using mathematic models, taking into account several criteria, namely: High average wind speed, regularity of the wind speed curve over the year, greatest capacity factor (C_f), maximum annual energy production (AEP). An economic analysis is carried out to determine the levelized cost of electricity (LCOE) as well as the LCOH.

The study's approach is divided into four major stages. In the first stage, a diagnosis of the current state of operational wind farms and those under construction is well established considering several parameters: installed capacity, technology deployed (type, power), capacity factor, investment, annual energy production, etc. In the second stage, site-related information such as latitude, longitude of the sites are collected, the wind speed data as well as the Weibull distribution are generated using WindPro software. Using mathematic models for assessing the capacity factor and annual energy production with the help of the Weibull distribution, and using a common type of wind turbine technology selected based on the diagnosis carried out, the best site for hydrogen production is determined. In the third stage, 2 other types of wind turbines are selected for subsequent analyses. Finally, the fourth stage of the study is the economic assessment of wind and hydrogen production.

2. Materials & Methods

2.1 Preliminary diagnosis

To determine the capacity factor (*Cf*), Table 3 provides a diagnosis of existing wind farms. According to Fig.10, this diagnosis provides a fluctuating capacity factor between 25% and 57%, which highly depends on the site specification (wind speed, roughness, wind regularity), the technology deployed (type, power, efficiency), the height and diameter of the blades. However, this diagnosis does not provide a correct determination of the capacity factor on the same comparative basis.

In fact, the average power (P_a) is calculated using the nominal electrical power (P_e) multiplied by *Cf* using (1). It can be determined either empirically or using a software (e.g. Windpro software) and P_e is calculated through the mathematical expression described in (2), defined by [56], based on the wind power (P_w) and the turbine efficiency (C_e), determined respectively by (3) and (4) according to [57,58]. It should be noted that this nominal electrical power depends on the surface swept by the blades as well as the efficiency of the generator (η_g), the multiplier (η_m) and the power coefficient (C_p), i.e. overall efficiency of about 80% [59].

$$P_a = P_e.Cf \quad (1)$$

$$P_e = C_e.P_w \quad (2)$$

$$P_w = \frac{1}{2}.\rho.S.v^3 \quad (3)$$

$$C_e = C_p.\eta_m.\eta_g \quad (4)$$

An analysis of wind farms under construction identified provides a focus on the southern and northern regions. Dakhla city will experience the construction of three sites with high wind potential, with an installed capacity of 340 MW (21%), followed by the site of Tetouan (19%), Boujdour, Essaouira (13%) and Laâyoune (11%) as shown in Fig.11.

Table 3. Specifications of operational wind farms in Morocco[60].

Site		Year of commissioning	Installed capacity (MW)
Tetouan	Koudia Baida	2000	54
	Lafarge	2000	10
	Lafarge +	2005	22
Tanger	Haouma	2009	50
	DahrSaadane	2013	107

	Bni majmel	2009	33
	Tanger II	2011	70
	Jbel khelladi	2017	120
Taza	Taza- Phase I	2022	87
Midelt	Midelt	2020	180
Essaouira	Amougdoul	2007	60
Tarfaya	Akhefennir 1	2013	101
	Akhefennir 2	2017	102
	Tarfaya	2014	301
Laâyoune	Cimar	2012	5
	Foum El aoued	2014	50
Boujdour	Aftissat	2019	200
	Boujdour	2022	300
Safi*	Oualidia	2021	36

(continued)

Site		Number of turbines	Technology
Tetouan	Koudia Baida	91	Vestas, Enercon
	Lafarge	12	Siemens Gamesa
	Lafarge +	11	Siemens Gamesa
Tanger	Haouma	22	Siemens Gamesa
	DahrSaadane	126	Siemens Gamesa
	Bni majmel	39	Siemens Gamesa
	Tanger II	31	Siemens Gamesa
	Jbel khelladi	40	Vestas
Taza	Taza- Phase I	27	GE Energy
Midelt	Midelt	42	Siemens Gamesa
Essaouira	Amougdoul	71	Siemens Gamesa
Tarfaya	Akhefennir 1	61	Ecotecnia
	Akhefennir 2	61	Ecotecnia
	Tarfaya	131	Siemens Gamesa
Laâyoune	Cimar	5	Siemens Gamesa
	Foum El aoued	22	Siemens Gamesa
Boujdour	Aftissat	67	Siemens Gamesa
	Boujdour	30	Siemens Gamesa
Safi*	Oualidia	12	Winwind W WD

(continued)

Site		Turbine unit power	Production (GWh/an)
Tetouan	Koudia Baida	0.6/0.5	200
	Lafarge	0.85	38
	Lafarge +	2	77
Tanger	Haouma	2.3	200
	DahrSaadane	0.85	390
	Bni majmel	0.85	120
	Tanger II	2.3	253
	Jbel khelladi	3	378
Taza	Taza- Phase I	3.2	313
Midelt	Midelt	4.3	560
Essaouira	Amougdoul	0.85	210
Tarfaya	Akhefennir 1	1.67	378
	Akhefennir 2	1.67	378
	Tarfaya	2.3	1084
Laâyoune	Cimar	1	16
	Foum El aoued	2.3	200
Boujdour	Aftissat	3	1000
	Boujdour	-	1000
Safi*	Oualidia	3	80

(continued)

Site		Investment in MDH	Cf (%)
Tetouan	Koudia Baida	526.76	42%
	Lafarge	101.3	43%
	Lafarge +	405.2	40%
Tanger	Haouma	810.4	46%
	DahrSaadane	2127.3	42%
	Bni majmel	658.45	42%
	Tanger II	972.48	41%
	Jbel khelladi	1722.1	36%
Taza	Taza- Phase I	1468.85	41%
Midelt	Midelt	2329.9	36%
Essaouira	Amougdoul	810.4	40%
Tarfaya	Akhefennir 1	1418.2	43%
	Akhefennir 2	1823.4	42%
	Tarfaya	5672.8	41%
Laâyoune	Cimar	101.3	37%
	Foum El aoued	810.4	46%
Boujdour	Aftissat	4052	57%
	Boujdour	4193.82	38%
Safi*	Oualidia	500	25%

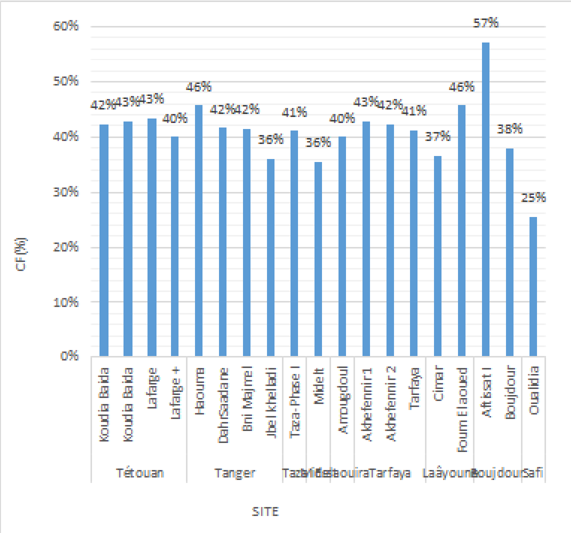

Fig. 10. Representation of capacity factors per site.

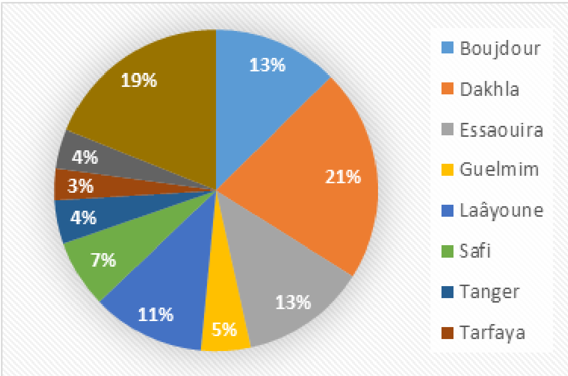

Fig. 11. Distribution of installed capacity among sites under construction.

Wind speed curve depends on the site specification; it presents an intermittence between day and night and it is strongly correlated with the hub height [61]. Recent studies have shown that a height of 100 m provides a reduction of this variability and ensures a regular operation [62]. In this context, the 9 sites are compared on a height of 100 m. Additionally, to ensure a comparative basis, the same technology with the same diameter and power is adopted, respectively Siemens Gamesa SG 2.2-122 whose technical specifications are reported in Table 4. Siemens Gamesa technology is one of the major emerging technologies for existing onshore wind farms; Fig.12 shows a predominance of Siemens Gamesa technology by 63%. Furthermore, the distribution of unit powers of wind turbines deployed in existing sites shows that an approximate power of 2MW is deployed for onshore wind farms; this is well illustrated in Fig.13 where the number of wind turbines of 2 MW installed in Morocco is predominant, about 35% (308/870).

Fig.14 shows the power curve for the adopted technology.

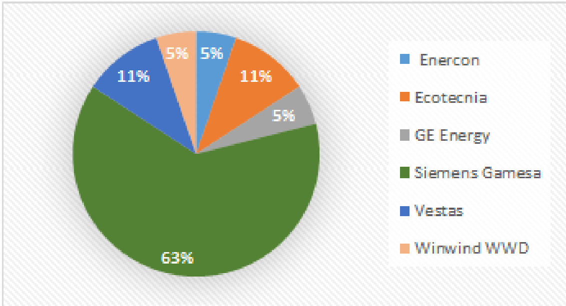

Fig. 12.Distribution of technology types deployed in existing sites.

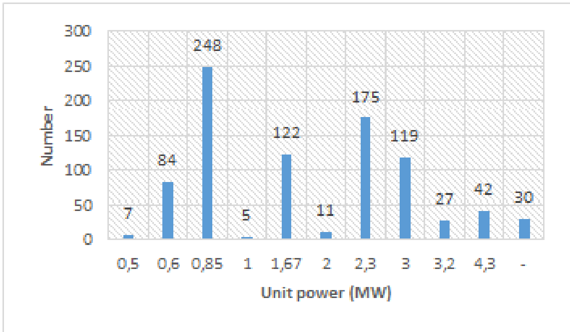

Fig. 13. Distribution of unit powers deployed in existing sites.

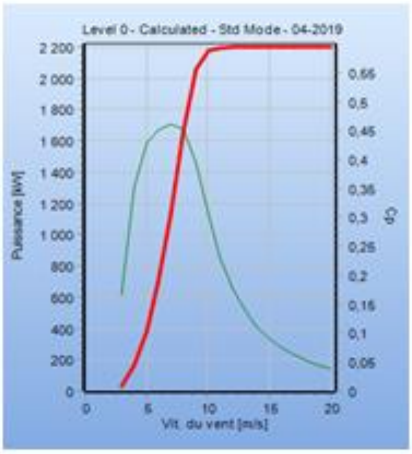

Fig. 14. Power curve for SG 2.2-122[63].

Table 3.Technical specifications of SG 2.2-122[64].

Height	**h**	**m**	**108**
Diameter	D	m	122
Swept area	A	m^2	11690
Cut-in wind speed	Vc	m/s	3

Cut-out wind speed	Vd	m/s	20
Rated wind speed	Vr	m/s	13
Rated power	P_r	MW	2.2

2.2 Site selection

According to Morocco's green hydrogen roadmap set out in 2021, a demand of up to **14 TWh** is expected by 2030: local hydrogen market of 4 terawatt hours (TWh) and an export market of 10 TWh [65]. In this context, the present work is carried out to respond to this demand.

WindPRO software [63] is used for the generation of wind data and Weibull distribution which will be used for the calculation of annual energy production and the capacity factor. A simulation is carried out for the 9 sites whose geographical coordinates as well as the average wind speed are represented on Table 5. From the hourly data of wind speed extracted at the height of 100 m over the past 10 years, a maximum annual average speed of 9.99 m/s is reported for the site of Tetouan followed by the site of Tangier, which presents a value of 8.72 m/s, Safi presents the lowest average speed reaching 6.17m/s (Fig.15). Fig.16 illustrates the monthly average values of wind speed (v) for the sites studied. Obtained by simulation, v records a maximum value fluctuating between 8.5 and 11 m/s in July for the sites of Essaouira, Tarfaya, Boujdour and Laayoune and a maximum wind speed reaching 10.8 m/s in March for the two sites of Tangier and Tetouan. Maximum wind speed are reported at 7.2, 8.5 and 8 m/s for Taza, Midelt and Safi in October, January and May respectively. In addition, v records a minimum value oscillating between 6 and 6.8 m/s in October for Tarfaya, Boujdour and Laayoune and a minimum wind speed up to 5 m/s in September for the two sites of Taza and Midelt. In addition, the site of Tetouan records a minimum wind speed in July reaching 9 m/s and minimum wind speed are identified: 7, 5.3 and 5 m/s for Tangier, Essaouira and Safi, respectively during the months of January and February.

The analysis of the statistical parameters (variance and standard deviation) shown in Table 6 reveals a low dispersion compared to the mean speed for the site of Tetouan. A high standard deviation is well reported for the site of Essaouira, which means that the values are widely dispersed around the mean forming a heterogeneous series. Moreover, according to Fig.16, the average wind speed curve in Tetouan is the most regular. Therefore, the management of intermittency will be reduced and the site of Tetouan is the most favourable and advantageous site.

Table 4. Geographical coordinates and average wind speed of the sub-study sites.

Site	Latitude	Longitude	Mean speed (m/s)
Tetouan	35.800079	-5.461890	9.99
Tanger	35.819359	-5.498006	8.72
Taza	34.2952628	-4.1264224	6.45
Midelt	32.7126721	-4.6531442	6.71
Essaouira	31.385053	-9.795598	7.71
Tarfaya	27.961425	-11.997644	7.18
Laayoune	27.018932	-13.388056	7.91
Boujdour	25.743	-14.592	8.54
Safi	32.753823	-8.945587	6.17

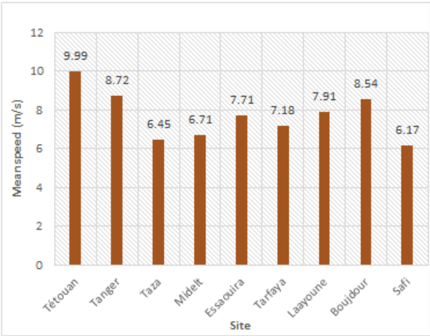

Fig. 15. Representation of the mean speed for the sub-study sites.

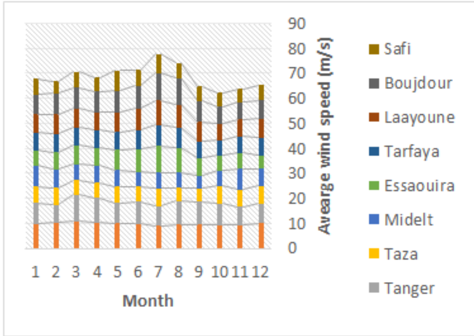

Fig. 16. Monthly average wind speed variation for the sub-study sites.

Table 5. Variance and standard deviation of the average wind speed.

	Tetouan	Tanger	Taza	Midelt	Essaouira	Tarfaya	Laayoune	Boujdour	Safi
Variance	0.30	1.05	0.45	0.99	2.54	0.47	0.89	1.61	0.83
Standard deviation	0.55	1.02	0.67	0.99	1.59	0.69	0.94	1.27	0.91

Figs. 17- 25 below give respectively the Weibull distribution curves during the last 10 years for each site studied. For the site of Tetouan, the most common wind speed is10 m/s, with a probability of 9.55%, whereas Tangier, Boujdour and Laayoune record a most common wind speed of 8m/s with a probability of about 12.59%, 13.7%, 14.91% respectively. For the sites of Taza and Tarfaya, the most common wind speed is about 7 m/s, with a probability of 11.72%, 16.48% respectively. Probabilities of 8.78%, 13.45% and 11.86% for respective speeds of 9 m/s, 6 m/s and 3 m/s are recorded for the sites of Essaouira, Safi and Midelt.

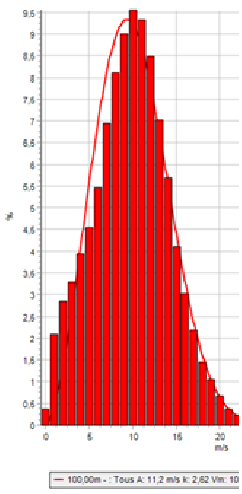

Fig. 17. Weibull distribution of wind speed in Tetouan at 100 m altitude.

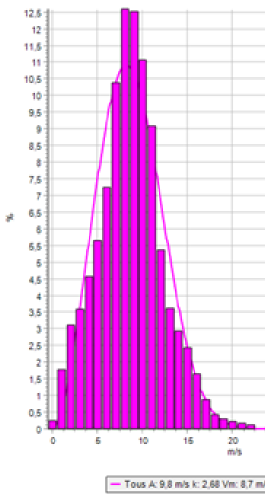

Fig. 18. Weibull distribution of wind speed in Tanger at 100 m altitude.

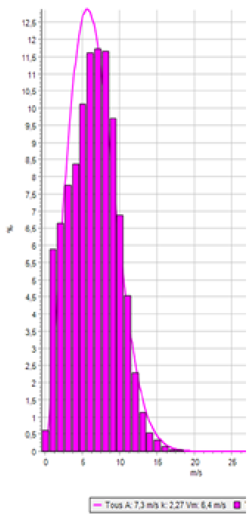

Fig. 19. Weibull distribution of wind speed in Taza at 100 m altitude.

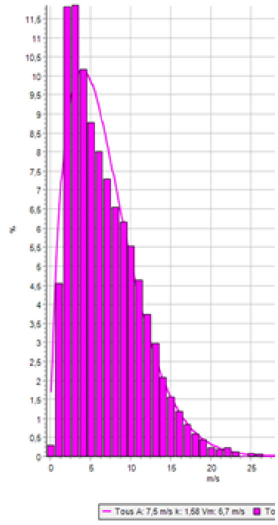

Fig. 20. Weibull distribution of wind speed in Midelt at 100 m altitude.

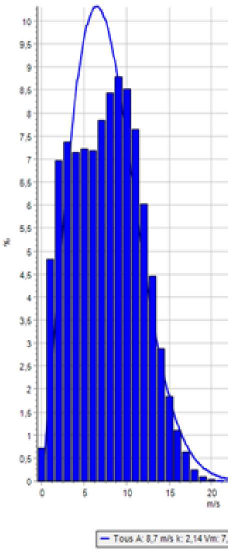

Fig. 21. Weibull distribution of wind speed in Essaouira at 100 m altitude.

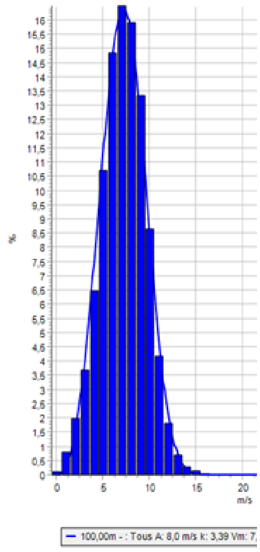

Fig. 22. Weibull distribution of wind speed in Tarfaya at 100 m altitude.

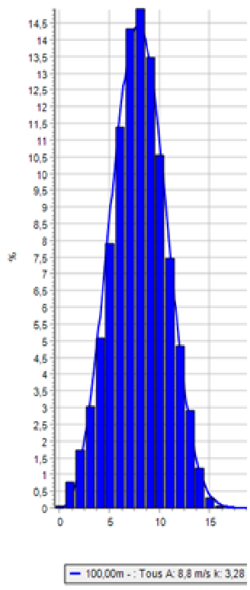

Fig. 23. Weibull distribution of wind speed in Laayoune at 100 m altitude.

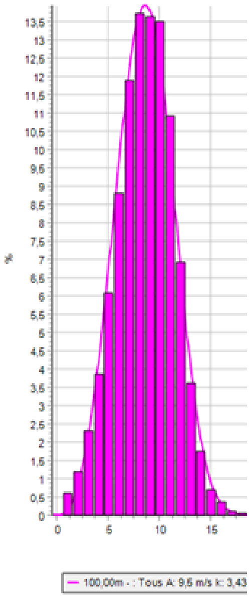

Fig. 24. Weibull distribution of wind speed in Boujdour at 100 m altitude.

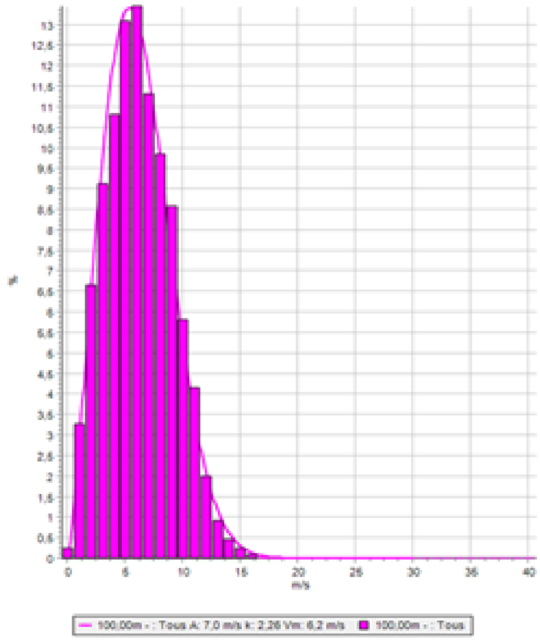

Fig. 25. Weibull distribution of wind speed in Safi at 100 m altitude.

On the basis of the hydrogen demand to be met (14 TWh), which is equivalent to an amount of 420 000 tons/year (determined on the basis of (5) and taking into account the lower heating of hydrogen (LHV) of 33.33 kWh/kg [66]), it is necessary to determine the required wind power potential expressed in kWh, according to (6) defined by [52,67]. For this purpose, an electrolyser with an energy consumption ($E_{electrolyser}$) of 61 kWh/kg is considered [68]. In general, electrolysers consume between 50 and 61 kWh/kgH_2 [47]. The electrolyser efficiency (η_{el})is estimated at 75% according to [69].

$$M_{H2} = \frac{D_{H2}}{LHV} \qquad (5)$$

$$E_T = \frac{M_{H2}}{\eta_{el}} . E_{electrolyser} \qquad (6)$$

Once the wind potential has been determined, the next step is to establish a comparative study between these sites based on the capacity factor which is defined as the ratio between the output power (P_a) and the nominal output power (P_r), calculated using (7) defined by [70]. It is known that the average power can be generated directly using a software or determined empirically using (8) and (9) (The superposition of the power curve of the adopted turbine technology and the frequency histogram generates the annual average wind power)[71]. Consequently, once the capacity factor is determined, the required power to install (P_{inst}) to respond to the wind potential needed (E_T) can be determined according to (10). The annual energy produced for a wind turbine is determined by (11). Nevertheless, this annual energy output does not include the uncertainties and losses that typically occur in a wind farm. Thus, it is necessary to determine the net annual energy produced (AEP_{net}) using (12) by applying all uncertainties and losses to the gross AEP reported as follows [72–74]:

- **Uncertainties (U)**: Wind turbine manufacturers give a 97% guarantee for their power curve, therefore a 3% uncertainty on the power curve has been assumed in the present work.
- **Wake effects losses**: present the influence on the energy production of the wind farm, which results from the changes in wind speed caused by the impact of the wind turbines on each other.
- **Availability losses**: This factor defines the expected average availability of the wind farm turbines over the life of the project. It represents, in percent, the factor to be applied to the gross energy to include the energy loss associated with the unavailability time of wind turbines to produce electricity. The availability of a wind power plant is assumed to be 98%, i.e. the plant is ready to produce power over 98% of the time the wind speed is within the operational range. It includes all unplanned shutdown of the plant, such as unplanned maintenance activities [75].
- **Electrical losses**: These are the electrical losses expected when the wind farm is operational and which will result in a reduction of energy.
- **Turbine performance losses**: This factor considers the expected shutdown of the turbines when the wind speed exceeds the cut- out wind speed value. High wind speed shutdown occurrences can create a significant endurance charge.
- **Environmental losses**: consider the extreme weather conditions that can affect the energy production of a wind farm, as well as the possible dirt that can be formed on the blades. Thus, the blade surface can be damaged over time.
- **Curtailment losses**: These are losses typically expected at wind farm sites located in or near forests or other areas covered by trees.

Table 7. Estimation of losses for onshore wind farms.

Losses	Average	Considered value
Wake effects	3-20%	7%
Availability	2-8%	2%
Electrical	2-4%	4%
Turbine performance	≤5%	5%
Environmental	2-5%	5%
Curtailment	1-3%	2%
TOTAL		22,5%

Various studies have revealed losses between 9.5% and 22.5%. Table 7 above shows the estimated losses for onshore wind farms. Thus, the number of wind turbines (N) required is determined according to (13).

$$Cf = \frac{P_a}{P_r} \quad (7)$$

$$P_a = \int P_e(v) f(v) dv \quad (8)$$

$$P_a = \sum_{v_i=v_c}^{v_d} P_e(v_i) H(v_i) \quad (9)$$

$$P_{inst} = \frac{E_T}{Cf.8760} \quad (10)$$

$$AEP = P_a.8760 \quad (11)$$

$$AEP_{net} = AEP.(1 - Losses).(1 - U) \quad (12)$$

$$N = \frac{E_T}{AEP_{net}} \quad (13)$$

2.3 Turbine technology selection

Once the advantagous site providing the best capacity factor and revealing the highest annual energy production (AEP) has been selected, the second part of the study is to compare three technologies (Siemens Gamesa, Vestas and Enercon) presenting the same power, approximately 2.2 MW, and the same diameter (≈122m), whose power curves are presented in Figs. 14-26-27. This will allow determining the most suitable model of wind turbine based on the annual energy production and high values of annual capacity factor. Table 8 represents the technical specifications of the three selected turbines.

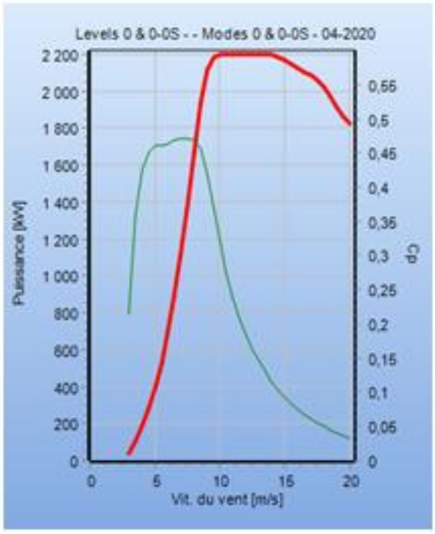

Fig. 26. Power curve for V-120/2.2[76].

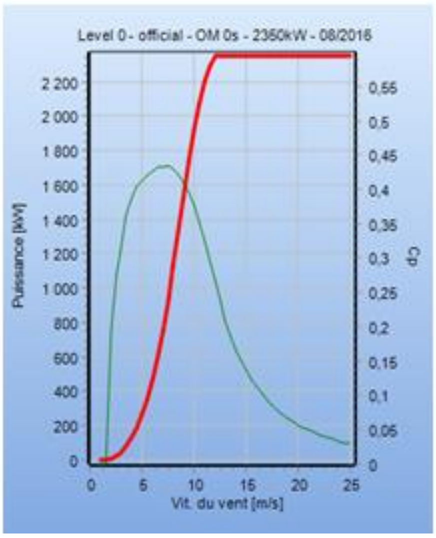

Fig. 27. Power curve for E-103/2350[77].

Table 6.Technical specifications of selected turbines[64,76,77].

Technology	Siemens Gamesa	Vestas	Enercon
Diameter (m)	122	120	103
Swept area (m²)	11690	11310	8332
Cut-in wind speed (m/s)	3	3	2
Cut-out wind speed (m/s)	20	20	25
Rated wind speed (m/s)	13	-	12
Rated power (MW)	2.2	2.2	2.35

2.4 Economic model

This section discusses the economic viability of the wind farm project as well as the hydrogen production. The investment cost (*I*) is generally expressed as a function of the selected wind turbine power rating, the specific cost (C_s) and the number of turbines installed in the wind farm (*N*) as shown in (13). Table 9 shows the specific cost of the wind turbine based on the rated power [78]. A specific cost of about 1300 $/kW is considered in this work [79].

$$I = N.P_r.C_S \qquad (14)$$

Table 9. Specific cost of the wind turbine based on the nominal power.

Rated power of turbine (kW)	Specific cost ($/kW)
10-20	2200-2900
20-200	1500-2300
>200	1000-1600

The investment cost includes mainly the cost of the turbine and equipment installation, site preparation and civil engineering, design and engineering costs, transportation and electrical installation costs. Fig.28 illustrates the distribution of the different components of the investment cost [56].

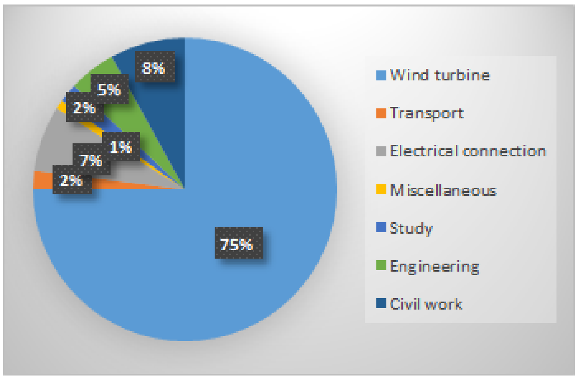

Fig. 28. Distribution of the different components of the investment cost [56].

In addition, the specific investment cost per kWh is determined according to (15) below in order to compare it with the specific investment cost obtained from Table 2, ranging between 0.26 and 0.62 $/kWh.

$$I_s = \frac{I}{E_T} \qquad (15)$$

The levelized cost of energy (*LCOE*) represents the actual cost of producing one kilowatt-hour (kWh) of electricity. It includes the total costs of installation, financing costs, lifetime expenses of the farm, capital return and depreciation. For electricity generation, LCOE is a method used to compare the renewable energy technologies adopted to generate electricity. According to IRENA, it is important to note that the *LCOE* for onshore wind farms has dropped by about 70% over the past 10 years, from **0.102 $/kWh** in 2010 to **0.033 $/kWh** in 2021 [80]. In Africa, the *LCOE* has reached an average of **0.055 $/kWh** [81].The objective is to reach **0.023 $/kWh** in 2030 according to GPRA (Government Performance and Results Act)[75].

Additionally, the *LCOE* is generally represented as a function of the initial investment capital (CapEx) amounting to 1300 $/kW, the annual energy produced AEP_{net} expressed in kWh/kW.year, fixed charge rate (*FCR*) expressed in % and determined according to (17), as well as the operating cost (OpEx) expressed in $/kW.year. It should be noted that this operating cost includes mainly the fixed operating costs (FC) and maintenance costs as well as the variable operating and maintenance costs (e.g. unscheduled maintenance of the park).

According to [82], the operating cost ranges from 33 to 59 $/kW.year, with an average of 46 $/kW.year. Therefore, the LCOE is calculated according to (16) below [75].

$$LCOE = \frac{(CapEx.FCR)+OpEx}{AEP_{net}} \quad (16)$$

$$FCR = \frac{r}{1-(1+r)^{-n}} \quad (17)$$

The lifetime of a wind farm is about 20 to 30 years [83]. A lifetime (n) of 25 years with a discount rate (r) of 5% are considered in the present work. The levelized cost of hydrogen, *LCOH* ($/Kg), is a function of electrolyser and electricity costs, $C_{electrolyser}$ and C_E, respectively expressed following (18) and (19). According to [84], (C_u) represents the unit cost, amounts to 1300 $/kW.(T) is the operation life of the electrolyser estimated at 13 years [85].Furthermore, [69] predict that the electrolyser life time will increase from 8 year in 2020 to 13,9 year in 2050 for PEM electrolyser and from 10 years to 15 years for AEL electrolyser. Therefore, the *LCOH* is expressed following the equation (20) defined by [86].

$$C_{electrolyser} = C_u.\ \frac{M_{H2}.E_{electrolyser}}{8760.Cf.\eta_{el}} \quad (18)$$

$$C_E = LCOE.\ \frac{\sum_{i=1}^{n} E_T}{n} \quad (19)$$

$$LCOH = \frac{C_{electrolyser}+C_E}{M_{H2}.T} \quad (20)$$

3. Results and Discussion

3.1 Site selection

To achieve a green hydrogen production of 14 TWh – 420 000 tons/year, the technical potential required from wind power is approximately 34 TWh. Table 10 details the main results of calculation for the 9 sites under study, mainly the gross and net annual energy produced, the average power, the capacity factor, the power to be installed and the number of turbines. The comparison of the calculated capacity factors (*Cf*) and those extracted from the diagnosis reveals a moderately low difference for most of the sites as shown in Fig.35. However, it should be noted that the site of Boujdour presents the best capacity factor, up to 57% according to the diagnosis, while the calculation revealed that the site of Tetouan has the strongest wind potential, with a capacity factor up to 55%, followed by Boujdour and Tangier.

The analysis of the results shows that the site of Tetouan offers a significant wind energy potential, which is more favourable to the exploitation of this type of energy for electricity production. It is the most suitable site, whereas Safi is the least qualified. The net annual energy production (AEP_{net}) amounts to 10.6 GWh. Thus, the installed capacity required is about 7 GW, i.e. a number of 3214 wind turbines with a unit power of 2.2 MW.

In addition, from an energy efficiency perspective, it is relevant to go beyond this comparison to estimate the gains in energy and GHG emissions avoided referring to the optimal site in terms of annual energy produced (AEP_{ref}). Therefore, Table 11 provides the energy gain generated (AEP_s), energy saving potential (*ESP*) as well as the avoided emissions (*AE*) for the 9 sites, referring to the Tetouan site as an exemplary site. In fact, a significant energy gain ranging between 0.33 and 4.5 GWh/year is highlighted, i.e. *ESP* between 2% and 32% and consequently a significant saving in annual emissions ranging from 243 teqCO_2 to 3307 teqCO_2, considering an emission factor (EF) up to 0.735 kgCO_2/kWh of electricity produced.

Table 7. Calculation results of energy parameters.

Site	*AEP* (kWh)	AEP_{net} (kWh)	P_a(kW)
Tetouan	**14 138 252**	**10 628 431**	**1 614**
Tanger	13 119 891	9 862 878	1 498
Taza	8 849 401	6 652 537	1 010
Midelt	8 317 416	6 252 617	949
Essaouira	10 819 916	8 133 872	1 235
Tarfaya	10 727 723	8 064 566	1 225
Laayoune	12 295 247	9 242 952	1 404
Boujdour	13 698 773	10 298 052	1 564
Safi	8 152 293	6 128 486	931
(continued)			
Site	**Cf (%)**	**Pinst (GW)**	**N**
Tetouan	**55.1%**	**7.1**	**3 214**
Tanger	51.2%	7.6	3 464
Taza	34.5%	11.3	5 135
Midelt	32.4%	12.0	5 464
Essaouira	42.2%	9.2	4 200
Tarfaya	41.8%	9.3	4 236
Laayoune	48.0%	8.1	3 696
Boujdour	53.4%	7.3	3 317
Safi	31.8%	12.3	5 575

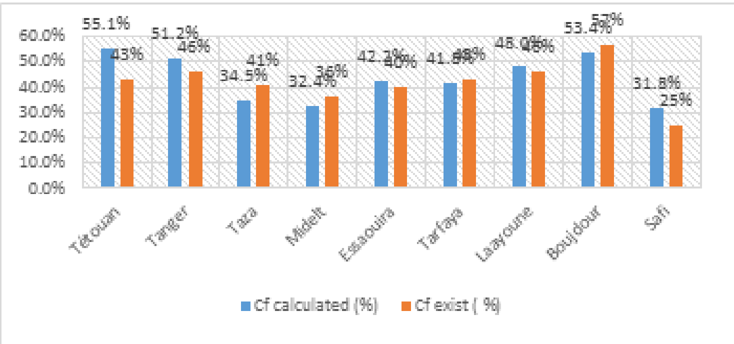

Fig. 29. Comparison of calculated and existing Cf resulting from diagnosis.

Table 8. Energy gain generated and ESP compared to the exemplary site.

Site	*AEP* (kWh)	AEP_{net}(kWh)	AEP_s(kWh)
Tetouan	**14 138 252**	**10 628 431**	-
Tanger	13 119 891	9 862 878	765 553
Taza	8 849 401	6 652 537	3 975 893
Midelt	8 317 416	6 252 617	4 375 813

Essaouira	10 819 916	8 133 872	2 494 559
Tarfaya	10 727 723	8 064 566	2 563 865
Laayoune	12 295 247	9 242 952	1 385 479
Boujdour	13 698 773	10 298 052	330 378
Safi	8 152 293	6 128 486	4 499 944
(continued)			
Site	***ESP*** **(%)**	***AE*** **(teqCO_2)**	
Tetouan	-	-	
Tanger	5%	562.68	
Taza	28%	2 922.28	
Midelt	31%	3 216.22	
Essaouira	18%	1 833.50	
Tarfaya	18%	1 884.44	
Laayoune	10%	1 018.33	
Boujdour	2%	242.83	
Safi	32%	3 307.46	

3.2 Turbine technology selection

In the second part, the simulation established with the following technologies: Siemens Gamesa, Vestas and Enercon, which have a similar power, approximately 2.2 MW, and similar diameter (122m) on the exemplary site (Tetouan), reveals a similarity in terms of capacity factor and annual energy production; a very marginal difference is noticed as it is shown in Table 12. Siemens Gamesa technology is considered as the exemplary technology (reference) for the following calculations.

A significant energy gain is highlighted when compared to the Enercon technology, amounting to 0.58 GWh/year, i.e. an ESP of 4% and 428 teqCO_2/year avoided.

Table 9. Energy gain and ESP compared to the exemplary technology.

Technology		***AEP*** **(kWh)**	***AEP_{net}*** **(kWh)**	***P_a*** **(kW)**
Siemens Gamesa	SG 2.2-122	**14 138 252**	**10 628 431**	**1614**
Vestas	V-120 2.2	14 091 648	10 593 397	1609
Enercon	E-103 2350	13 363 161	10 045 756	1525
		(continued)		
	Cf (%)	**AEPs (kWh)**	**ESP (%)**	**AE (teqCO_2)**
	55.1%	-	-	-
	55.0%	35 034	0.2%	25.75
	48.8%	582 675	4.1%	428.27

3.3 Economic Assessment

The economic assessment reveals a specific investment (*Is*) of 0. 27 $/kWh (see Table 13), which is within the range obtained from Table 2, between 0.26 and 0.62 $/kWh. Additionally, for a CapEx of 1300 $/kW and an operating cost (OpEx) of 46 $/kW.year, the *LCOE* is about 0.029 $/kWh. It should be noted that this cost is very competitive compared to previous studies. In fact, a levelized cost of energy up to 0.038 $/kWh has been determined from an onshore wind farm in the Tiznit province in Morocco [70]. Moreover, [49,50] declined respectively a value of *LCOE* ranging from 0.0694 to 0.133 $/kWh for five sites in the Republic of Djibouti and between 0.0398–0.0801 $/kWh in 18 locations in the Sultanate of Oman .It is worth noting that the resulting *LCOE* aligns with the GRPA's stated purpose (to reach 0.023 $/kWh in 2030).

Compared to the existing state, this reveals a production gain of 0.004 $/kWh, i.e. 271 338 $/year. See Tables 14-15 for detailed calculation of *LCOE* and total energy gain (*TEG*).

Table 13. Specific cost investment.

Site	*AEP (kWh)*	*Cf*	*Pinst*
Tetouan	10 628 431	55.1%	5.6
(continue d)			
CapEX	***I***	***Is***	***Is exist***
1300	7 257 647 012	0.27	0.26 -0.62

Table 14. Calculation of the LCOE.

Site	CapEX	AEP_{net} (kWh/kW.year)	FCR (%)
Tetouan-Improved	1300	4831	7%
Tetouan-Existing	1034	3700	7%
	OpEX ($/kW.year)	***LCOE* ($/kWh)**	
	46	0.029	
	46	0.032	

Table 15. Production energy gain compared to the existing state.

Site	*LCOE* ($/kWh)	*EG* ($/kWh)	*TEG* ($)
Tetouan-Improved	0.029	-	-
Tetouan-Existing	0.032	0.004	271 338

Considering an optimal LCOE of 0.029 $/kWh, the levelized cost of Hydrogen (*LCOH*) is about **1.86 $/kg**. The result shows that using wind turbines provides low-cost hydrogen in Morocco, especially in Tetouan. It's the lowest cost in Morocco compared to previous studies; as an example of the study that has been conducted to determine the *LCOH* from wind turbine and PV panel's combination. The most significant LCOH has been determined for Dakhla city, an amount of 2.54 $/kg [44]. Furthermore, recent studies established in the Sultanate of Oman and the republic of Djibouti reveal a LCOH from wind equal to 3.37–6.13 $/kg and ranging from 1.79 to 3.38 $/kg, respectively . Whereas, a very competitive levelized cost of hydrogen, reaching 1.214 $/kgH$_2$ is reported in Algeria. Based on these results and according to [87], the *LCOH* depends mainly on the LCOE, the type of electrolyser, CapEx and the capacity of the electrolyser. In particular, the cost of the electrolyser has the greatest influence. Indeed, it has been estimated that a 70% cost reduction in electrolysis technologies would enable to reduce the cost of the LCOH by 1€/kg [88]. In addition, the accelerating production of electrolysers will reduce the cost of green hydrogen [89]. It could be claimed that the future success of green hydrogen is determined by the technological development of electrolysers.

4. Conclusion

To achieve a green hydrogen production of 14 TWh according to Morocco's roadmap, the technical potential required from wind power is approximately 34 TWh. This study aims to identify the best location where we can produce this amount of energy with a maximal energy production, best capacity factor and a minimal LCOH. For this purpose, based on wind speed measurements recorded over a period of ten years for the 9 sites and adopting SG 2.2-122 technology, a first comparison between the sites was established. It shows that the site of Tetouan provides a high wind potential compared to other sites with a better capacity factor of 55%. In this location, the required capacity to install in order to reach the hydrogen demand is about 7 GW. An energy saving potential ranging between 2% and 32% is well reported, equivalent to a significant energy gain ranging between 0.33 and 4.5 GWh/year and a significant annual emission saving ranging from 243 teqCO_2 to 3307 teqCO_2. A second comparison was conducted for the selected site based on the selection of the best technology to adopt. The simulation conducted using three technologies (Siemens Gamesa, Vestas and Enercon) of similar power, diameter and hub height, reveals that Siemens Gamesa technology is the most advantageous and appropriate by offering a better capacity factor and maximum energy production. A significant gain in energy is underlined up to 0.58 GWh/year, 35 MWh/ year compared respectively to Enercon and Vestas technologies. The economic evaluation revealed a significant *LCOE* of 0.029 $/kWh and an *LCOH* of 1.86 $/kg for wind-to-$H_2$ production in Tetouan. The limitation of this study is that other factors such as the proximity to water sources for electrolysis process and the proximity to gas pipeline to export the hydrogen produced were not considered for site selection. Future study would compare sites with high wind potential considering other specific parameters in addition to wind speed using GIS-MCDM technique.

Nomenclature

AEP	Annual energy production
AHP	Analytic hierarchy
CO_2	Carbon dioxide
CRI	Commercial readiness index
GHG	Greenhouse gases
GIS	Geographic information system
GW	Gigawatt
GWh	Gigawatt hour
IEC	International Electrotechnical Commission
IRENA	International Renewable Energy Agency
IRESEN	Research Institute for Solar Energy and New Energies
LCOE	Levelized cost of energy
LCOH	Levelized cost of hydrogen
MASEN	Moroccan agency for sustainable energy
MCDM	Multi criteria decision making
MDH	Million of dirhams
MENA	Middle East and North Africa
MT	Million tons
MW	Megawatt
NDC	Nationally Determined Contributions
OCP	Office chérifien du phosphate
PJ	Petajoule
SMR	Steam methane reforming
TES	Total energy supply
TRL	Technology readiness level
TWh	Terawatt hour

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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