

# Energy, economic and environmental assessment of green hydrogen production from wind energy at the university

*Naoufal El Ghouch<sup>1\*</sup>, Aicha Chorak<sup>2</sup>, and Fatima Bahraoui<sup>1</sup>*

<sup>1</sup>MaSEEL, FST of Tangier, Abdelmalek Essaâdi University, Tangier, Morocco

<sup>2</sup>Laboratory of Systems, Control, and Decision (LSCD), New Science School of Engineering (ENSI), Tangier, Morocco.

**Abstract:** This work proposes an energy, economic and environmental assessment of green hydrogen production from wind energy at the Faculty of Sciences and Techniques (FST) of Tangier. Through the analysis of wind conditions, the selection of a Bergey Excel 10 wind turbine (10 kW), an AEM EL 4.1 electrolyzer and a BMW i3 battery storage system, the project demonstrates the feasibility of an autonomous clean hydrogen production system. The results indicate an annual electricity production of 13,351.2 kWh, generating 249.89 kg/year of hydrogen, with a CO<sub>2</sub> emission reduction of 9,157.58 kg/year and an estimated return on investment of 13 years.

**Keywords:** Green hydrogen; Wind energy; Electrolysis; Weibull distribution; Energy storage; Energy transition.

## 1 Introduction

The global energy transition is one of the major challenges of the 21st century. Faced with the depletion of fossil resources and the worsening of climate change, governments, institutions and industrial actors are compelled to rethink their energy production and consumption systems. Morocco, aware of its vulnerability to energy imports and its potential in renewable resources, has adopted an ambitious strategy aimed at raising the share of renewable energies to 52% of its installed electricity capacity by 2030 [1].

In this context, green hydrogen produced by electrolysis of water powered exclusively by renewable energy sources, emerges as a promising energy carrier. It offers the dual capacity to store intermittent electrical energy and to decarbonize sectors that are difficult to electrify directly, such as industrial chemistry, heavy transportation and ammonia production.

Wind energy, abundant in Morocco and specifically in the Tangier region, holds promise in the generation of green hydrogen through its coupling with electrolyzers. Coupling wind power with electrolyzers mitigates the fluctuations associated with wind energy utilization while benefiting from surplus production [2,3,4]. Morocco has a wind energy potential exceeding 25,000 MW, which is mainly found in the regions of Tangier, Tarfaya, and Essaouira. The road map for green hydrogen issued by the Ministry of Energy of Morocco envisages the country as a future exporter of green hydrogen to Europe. In terms of environmental analysis, the combination of wind and electrolyzers is seen as one of the alternatives that have a significantly lower GWP and AP than traditional natural gas [2]. The literature review concerning the area of wind-hydrogen hybrids has greatly increased over the past two decades [4]. The underlying concepts regarding the incorporation of electrolysis in wind energy generation were studied by scientists, explaining the problems associated with the coordination of the intermittency of the wind energy with the efficiency of electrolyzers. Additional studies revealed that the Weibull function can be applied accurately in the analysis of the wind characteristics.

\* Corresponding author: [naoufalelghouch@gmail.com](mailto:naoufalelghouch@gmail.com)

Successful pilot programs include the PURE program of Orkney Islands in Scotland, the HARI program (hydrogen and renewables integration) in the United Kingdom, and, more recently, large-scale projects in Germany and the Netherlands. These programs confirm that the wind-hydrogen technology is technically feasible and demonstrate the importance of proper sizing [2]. There exist three commercially available electrolysis technologies today. Among all the three electrolysis methods, alkaline electrolysis (AWE) is the most developed technology that uses potassium or sodium hydroxide as an electrolyte. This technology is best suited for large-scale operation. PEM technology, which can be operated at a high current density and dynamic response, has an advantage in its application for fluctuating load conditions, mainly in renewable energy generation systems. Lastly, SOEC, which is in its developmental phase, can attain high efficiency but operates at elevated temperatures of 800–1000°C [6,7,8,9,10].

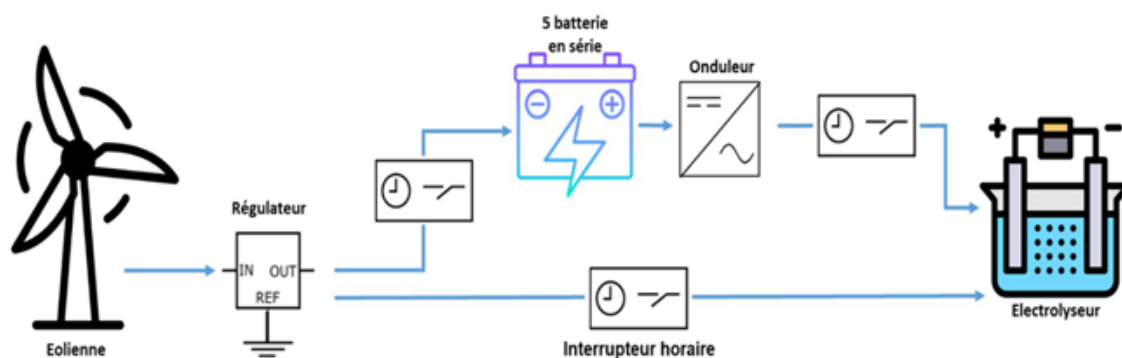
Similarly to any other educational establishment, the soaring energy costs and pressures of reducing their carbon footprint are critical concerns in Moroccan universities. Such situation pertains to the Tangier's Faculty of Science and Technology, which is a scientific and technical educational establishment that depends greatly on energy generated using power stations fueled by fossil fuel sources. Two basic concerns emerge in this context:

- Variability of energy generation through wind: power is produced from wind mills only when the wind blows at a suitable speed. It becomes difficult to integrate this energy directly into the grid without some method of storing it.
- Storing the excess energy generated: existing batteries for storing energy have limitations on their capacity and longevity. Hydrogen, due to its high mass density, provides a good option.

The present paper fits into this trend with the design of an integrated assessment of energy, economic, and environmental impact of green hydrogen production from wind energy. This study will help validate the feasibility and economic benefits of such a wind plant along with its environmental impacts. Therefore, the core question which will guide this research effort can be formulated as follows: How feasible, economically attractive, and environmentally beneficial would be the use of a wind plant integrated with electrolysis and batteries on the Tangier campus of FST.

## 2. Methodology

### 2.1 structure of the production system



**Figure 1.** Structure of the system of production

This section presents the schematic diagram of a green hydrogen production plant that uses wind energy. Since wind energy can be intermittent, the electricity generated from wind turbines is passed through a voltage regulator to ensure constant flow of electric current. The regulated electric current is then used to charge a set of five batteries that are connected in series with the use of a timer circuit to prevent overcharging of the battery cells. The electrical energy stored in the battery cells is then converted into alternating current through an inverter which is fed to the electrolyzer where electrolysis of water ( $H_2O$ ) produces pure  $H_2$  gas.

## 2.2 Wind resource analysis

Wind velocity data at the Tangier site of FST were obtained using the RETScreen tool on a monthly basis [17]. The statistical model used is that of the Weibull distribution with two parameters, with its probability density function expressed by the formula below [1]:

$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} * e^{-\left(\frac{v}{c}\right)^k} \quad (1)$$

The shape parameter  $k$  and scale parameter  $c$  were estimated from the monthly mean wind speed ( $\bar{v} = 5.508$  m/s) and standard deviation ( $\sigma = 0.24$  m/s), yielding  $k = 30$  and  $c = 5.49$  m/s. The probability of wind speed being between 5 and 6 m/s, the optimal operating range of the selected turbine, reaches 94.12%, confirming the excellent suitability of the site. The expected power per unit area was calculated numerically in MATLAB, yielding  $Pe = 96.41$  W/m<sup>2</sup> [10,11,12].

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \quad (2)$$

$$c = v_m \left(1 + \frac{1}{k}\right)^{-\frac{1}{k}} \quad (3)$$

$$Pe = \frac{1}{2} * \rho * \int_0^{\infty} v^3 * f(v) dv \quad (4)$$

$$\rho = 1,25 \text{ kg/m}^3$$

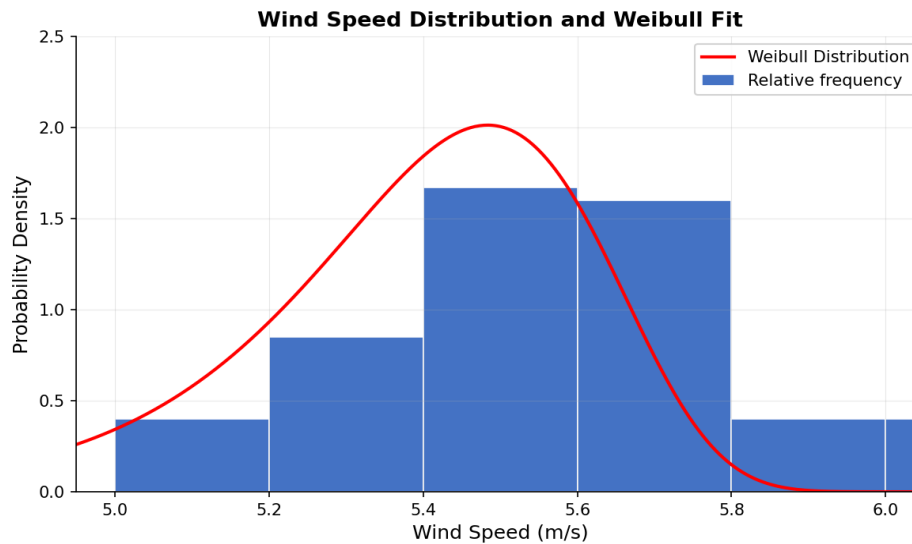
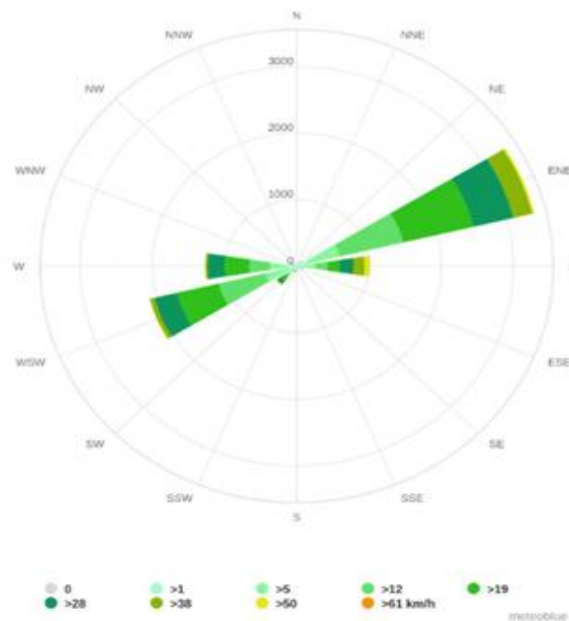


Figure 2. Distribution of weibull

## 2.3 Equipment selection and sizing

The wind turbine chosen is the Bergey Excel 10 (10 KW rating). This is a three-bladed horizontal-axis wind turbine that has proven reliable in residential and institutional settings. The features of the wind turbine (cut-in wind speed of 2.5m/s, wind speed of 12m/s, permanent magnet generator) make it well suited for use in the region.

The wind rose of Tangier (Fig. 3) indicates a dominant ENE direction, thus orienting the installation to maximize kinetic energy capture.



**Figure 3.** Wind rose of Tangier

Electrolyzer chosen is the Enapter AEM EL 4.1, which works based on AEM (Anion Exchange Membrane) technology. The production capacity of the system reaches 500 NL/h, with hydrogen purity at 99.9% under 35 bar pressure. The specific consumption amounts to 4.8 kWh/Nm<sup>3</sup>, while efficiency is estimated at 73.75%. The system operates using alternating voltage 220-240V, suitable for a turbine supply with inverter [13].

The electrical storage, intended to power the electrolyzer during periods of insufficient wind, is provided by 5 BMW i3 48V 63Ah battery modules (NMC technology) connected in series, offering a voltage of 240 V and a total capacity of 15 kWh, exceeding the maximum energy to be stored (14.3 kWh in January and August).

## 2.4 Economic and environmental analysis

The economic analysis relies on a cost-benefit calculation involving investment costs (wind turbine, electrolyzer, batteries, controller, inverter, cables), yearly operational costs (maintenance, water) and revenue generation from the commercialization of the hydrogen gas generated (50 DH/kg). The rate of return on investment is computed through the use of the payback period formula. The ecological effect is determined in terms of carbon dioxide emissions savings, which is obtained by subtracting the CO<sub>2</sub> emissions from the traditional energy mix (0.7 kgCO<sub>2</sub>/kWh) from the emissions from the wind-powered energy system (0.0141 kgCO<sub>2</sub>/kWh).

## 3 Results and Discussion

### 3.1 Electricity production

This wind turbine produces annually 13,351.2 kWh of energy on average with the power of 18.05 kW per month accumulated in a year. The high stability of monthly productivity coefficients ranging from 0.360 to 0.367 shows that the wind turbine perfectly fits into the local wind profile. It is worth noting that the month in which productivity is the highest is March (1,339.2 kWh) while January and August produce the lowest energy levels (967.2 kWh each) [14].

### 3.2 Hydrogen production

Table 1 gives the annual output of hydrogen. The production of electricity per month was determined by using the performance coefficient  $C_p$  obtained from the graph provided by the manufacturer of the wind turbine. Annual output is the sum total of outputs per month. The output of hydrogen is calculated based on the efficiency of the electrolyzer, taking into account the time the system operates and stores energy.

**Table 1.** Annual production of hydrogen

Month	Production kW	Daily Production kWh/day	Operating Duration h	Storage Duration h	Storage Energy kWh	Required Power kW	Electrolyzer Consumption kWh	H <sub>2</sub> Production kg/day	Annual H <sub>2</sub> Production kg/year
January	1.3	31.2	13	11	14.3	1.1	2.4	0.5841875	18.10
February	1.7	40.8	17	7	11.9	0.7	2.4	0.7639375	21.39
March	1.8	43.2	18	6	10.8	0.6	2.4	0.808875	25.07
April	1.7	40.8	17	7	11.9	0.7	2.4	0.7639375	22.91
May	1.5	36	15	9	13.5	0.9	2.4	0.6740625	20.89
June	1.6	38.4	16	8	12.8	0.8	2.4	0.719	21.57
July	1.7	40.8	17	7	11.9	0.7	2.4	0.7639375	23.68
August	1.3	31.2	13	11	14.3	1.1	2.4	0.5841875	18.11
September	1.4	33.6	14	10	14	1	2.4	0.629125	18.87
October	1.5	36	15	9	13.5	0.9	2.4	0.6740625	20.89
November	1.4	33.6	14	10	14	1	2.4	0.629125	18.87
December	1.4	33.6	14	10	14	1	2.4	0.629125	19.50
<b>TOTAL</b>									<b>249.89</b>

In one year, the output of hydrogen is 249.89 kg/year, which corresponds to 3,033,966.98 litres of hydrogen gas at 25°C (or 2,778.86 normal cubic metres at 0°C). The operation process, with the electrolyzer running for between 13 and 18 hours daily, along with 6 to 11 hours battery storage per day, makes it possible to consume all the generated power.

A result summary from the wind-to-hydrogen project is provided in Table 2. Although the wind potential is moderate, the environmental and economic viability of the system proves quite high. With an average wind speed of 5.508 m/s, this project can produce an annual electricity of 13,351.2 kWh, generating almost 250 kg of green hydrogen. Environmentally, this project avoids the production of more than 9.1 metric tons of CO<sub>2</sub> annually. Economically, a total initial capital investment is necessary in order to start this project; however, the payback period of 13 years would amount to a net gain of 78,432 DH.

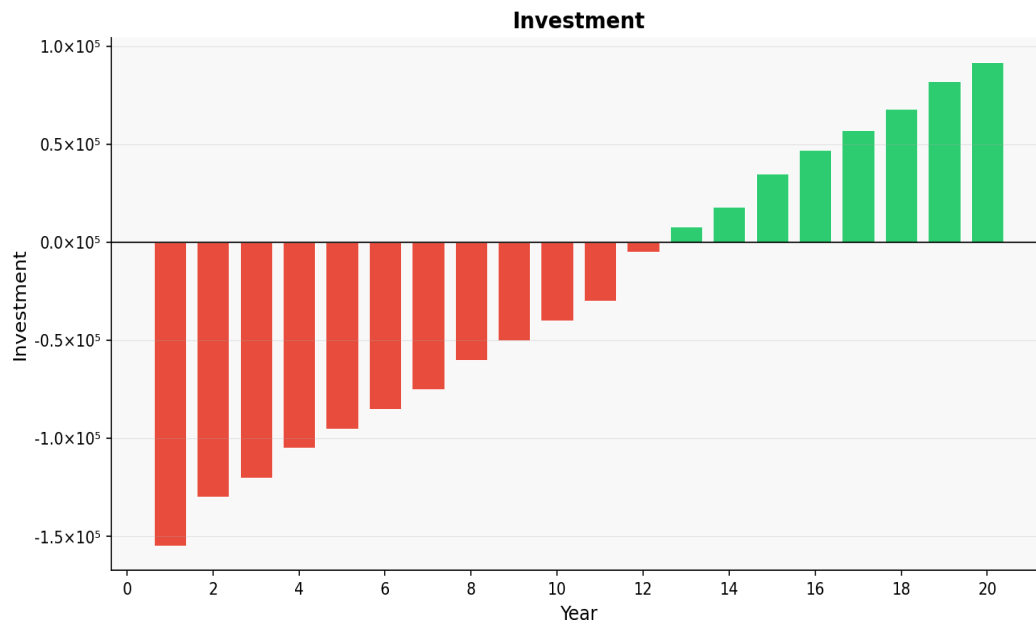
The FST Tangier study can be compared to a feasibility study that analyzed small wind-hydrogen systems at Ghardaïa University, Algeria [15]. Although Ghardaïa has better desert winds (6–7 m/s compared to Tangier's 5.51 m/s), produces more hydrogen gas (285–375 kg/year compared to 249.89 kg/year), and achieves this largely by increasing tower heights (30–60 m produces a 31% increase in hydrogen produced), the Tangier system is more economically viable with a return on investment of 13 years at a cost of only 155,150 DH. The two studies indicate the potential in North Africa for green hydrogen generation from wind power, although unlike Ghardaïa, Tangier benefits from battery energy storage (15 kWh BMW i3 modules).

**Table 2.** Wind-to-hydrogen project results summary

Parameter	Value	Unit
Annual electricity production	<b>13 351,2</b>	kWh
Average wind speed	<b>5,508</b>	m/s
Annual hydrogen production	<b>249,89</b>	kg/an
Annual hydrogen volume (25°C)	<b>3 033 966,98</b>	litres/an
CO <sub>2</sub> avoided per year	<b>9 157,58</b>	kg/an
Return on investment	<b>13</b>	ans
Net gain over 20 years	<b>78 432</b>	DH
Total investment	<b>155 150</b>	DH

### 3.3 Economic analysis

The total project investment amounts to 155,150 DH, broken down mainly between the wind turbine (86,000 DH), the electrolyzer (50,000 DH) and the batteries (11,160 DH). With an estimated annual revenue of 12,494.88 DH (from the sale of produced hydrogen, after deducting operating costs), the project reaches its break-even point after 13 years (Fig. 4). Over the 20-year lifespan of the wind turbine, the cumulative net gain amounts to 78,432 DH, demonstrating significant medium-term profitability.



**Figure 4.** Investment Diagram

These figures should be put in perspective with the likely evolution of the cost of green hydrogen. International projections anticipate cost parity with fossil hydrogen by 2025–2030, which would significantly enhance the commercial value of local production.

### 3.4 Environmental impact

The quantity of CO<sub>2</sub> that could be prevented through this process amounts to 9,157.58 kg annually, which can be equated to the carbon footprint left by the burning of over 3,700 litres of gasoline. This figure was verified using an online carbon footprint calculator, where the CO<sub>2</sub> amount emitted from generating 13,351 kWh was found to be around 8.73 tonnes of CO<sub>2</sub>. This translates to approximately 183 tonnes of CO<sub>2</sub> saved within a span of two decades, which constitutes a significant benefit for the environmental goals of the university and country.

### 4 Conclusion

This study has demonstrated the technical, economic and environmental feasibility of a green hydrogen production system powered by wind energy at the FST Tangier University site. Through rigorous analysis of local wind resources using Weibull modeling, optimized sizing of the Bergey Excel 10 wind turbine, the AEM EL 4.1 electrolyzer and the BMW i3 battery bank, the system is capable of producing 249.89 kg/year of green hydrogen, while avoiding the emission of 9,157.58 kg of CO<sub>2</sub> per year.

In terms of economics, although the cost of installing this renewable energy production system is 155,150 DH, the payback period of this investment is 13 years, and the net profit is 78,432 DH. Moreover, the decreasing cost of green hydrogen technology, along with these promising results, makes projects of this kind very appealing to universities and higher education institutions.

Several research avenues have been raised in this paper, which includes the development of a system coupling photovoltaics and wind, improving energy management using artificial intelligence techniques, and evaluating the valorization of oxygen produced simultaneously during electrolysis. On a more general scale, this example can motivate the design of hydrogen micro-grids for universities in other parts of Morocco.

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