Techno-economic investigation of electricity and hydrogen production from wind energy in Casablanca, Morocco

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Abstract: The aim of this study is to investigate the technical and economic potential of electricity and hydrogen production in Casablanca, Morocco. For this reason, we simulated the performance of a 4.2 MWp wind turbine if installed in Casablanca. The results show that the electricity and hydrogen production varies greatly through the year due to the high fluctuation in wind speed. The annual electricity and hydrogen production is 29.16 GWh and 555 Tons respectively. As for the levelized cost of production, the $LCOE$ was found to be 0.24 $$/kWh and the $LCOH_2$ were equal to 13.52 $$/Kg.

Keywords: Wind energy; Electricity production; Hydrogen production; Simulation; Economic analysis.

1. Introduction

Wind power technologies has known a significant development in the last decade. Indeed, between 2008 and 2017 several aspects of the technologies have been improved such as higher hub heights and larger areas swept by blades. This development was accompanied with a reduction of the wind turbines prices. The global installed wind capacity has increased as well, in fact from 2000 to 2016 the cumulative installed capacity increased by an annual rate of 15% to reach 467 GW by the end of 2016 [1].

In addition to electricity production, wind energy can also be used to generate hydrogen via the water electrolysis process, which consist of splitting the water molecule under the effect of electric current. In this context, the wind turbine is coupled with an electrolyzer to achieve that goal. The water electrolysis process has many advantages: it is a mature and well-established technology with a high energy efficiency, it produces hydrogen with high efficiency, and it has a has a perfect compatibility with renewable energy such as wind energy [2]. Therefore, the hydrogen produce in this case can be considered as “green and clean” and can be regarded as a sustainable substituent for fossil fuels.

Indeed, hydrogen can generate 3 time more energy than all other fuels, it can be used in most application that require fossil fuels and it release only water during its combustion [2]. Besides, a wide range of applications in the industrial sector uses hydrogen for their process such is the case for the fertilizer industry, food industry, petroleum industry, glass purification etc.[3].
Regarding the wind energy status in Morocco, the country has set an objective to produce 14% of its electricity need from wind energy by 2020. This ambitious goal was steam from the fact the Morocco is a fossil fuel deficient country (import more than 96% of its energy needs), but in the other hand, has a high wind energy potential especially in the coastline where the mean wind speed can reach up to 10 m/s [4–7]. Accordingly, various large scale wind farms are currently being constructed under a ten year project called the Moroccan Integrated Wind Energy Project (MIWEP) which aim to expand the wind energy capacity to 2000 MW by 2020 [6].

Many researchers has investigated the electricity and hydrogen production from wind energy in various locations. For instance, Mohsin et al. [8] conducted an assessment of wind energy potential for electricity and hydrogen production in Karachi region, Pakistan. They found a levelized cost of electricity in the range of 0.0844-0.0864 $/kWh and a supply cost of hydrogen between 5.30 $/Kg and 5.80 $/kg. Genç et al. [9] investigated the hydrogen production for 3 wind turbines with different hub height (50, 80 and 100 m) in Pınarbaşı-Kayseri, Turkey. The results shows that with the increase of the hub height, the hydrogen production increase as well while the cost of the production decrease. Also, the maximum hydrogen production and the minimum cost were found to be 14192 Kg/year and 8.5 $/Kg respectively, both in the case of the 100 m turbine. Siyal et al. [10] estimated the potential of hydrogen production from wind energy in Sweden. The authors found that a 25,580 ktons could be produce annually, which is equivalent to 860 TWh of energy. Rahmouni et al. [11] found that the potential of electricity and hydrogen production from wind energy in Algeria is in the range of 48-1074.8 GWh/km² and 842.62-18447.6 Tons/km²/year respectively.

In this study, we investigated the electricity and hydrogen production from wind energy in Casablanca. To this end, we simulated the performance of a 4.2 MWp wind turbine under the climate of Casablanca. To achieve that goal first, we briefly describe the simulated system and the tool used, then the methodology followed for the estimation of the hydrogen production as well as the cost of production of electricity and hydrogen, and finally we present the results.

2. Methodology

In this part, we will first describe the general characteristics of the wind turbines than the technical data of the one selected for simulation, afterwards, we present the simulation software for the electricity production then the methodology to estimate the hydrogen production, and finally the metrics used for the economic analysis.

2.1 System description

The electricity production from wind energy is directly proportional to the wind speed, and in order to convert wind energy into electricity, wind turbines are used [12]. Depending on the axe of rotation, wind turbines can be divided into two categories: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). The HAWTs are the most used by the wind industry and almost entirely for the utility scale wind market since they offer higher efficiency and energy production than the VAWTs [1,12,13].

Typically, wind turbines are made of the following components [13]:

- **Rotor**: generally, its composed of three large blades similar to the airplane wing.
- **Nacelle**: connected to the rotor at the top of the wind turbine, and can rotate in accordance with the wind direction for a maximal harness of wind energy. In addition, it carries the principal technical parts like gearbox, and generator.
- **Gearbox**: increase the rotor speed to meet the generator requirement to produce electricity.
- **Generator**: used for the conversion of the mechanical energy from the rotor to electricity.

The main parameters that influence the electricity production from the wind turbine are height and the rotor diameter. Also, the wind turbine require a minimal wind speed to start generating electricity which is generally ranges between 3 and 5 m/s and for a wind speed around 25 m/s the wind turbine cut out, as for the maximum power production is reached for 11-12 m/s [1].
In this study, we simulated the performance of the Enercon E-126 EP4 under the climate of Casablanca, Morocco. The characteristics of the wind turbine are presented in table 1.

Table 1. Characteristics of the wind turbine (Enercon E-126 EP4)

| Characteristics          | Value     |
|--------------------------|-----------|
| Hub height (m)           | 135       |
| Rated power (kW)         | 4200      |
| Swept area (m$^2$)       | 12667     |
| Cut-in speed $V_{cin}$ (m/s) | 3       |
| Rated speed $V_r$ (m/s)  | 14        |
| Cut-out speed $V_{cout}$ (m/s) | 25      |

2.2 Simulation software

Simulation is a widely used method for the prediction of the performance of renewable energy systems. In this study, the Green Energy System Analysis Tool (Greenius) developed by the German Aerospace Center (DLR) is used to simulate the electricity production from the wind turbine. Greenius is a powerful tool for the simulation of renewable energy projects such as solar and wind that allow the entire definition of the energy system by the user, and provide a realistic simulation results in different time steps [14]. Accordingly, many studies has used Greenius to simulate various energy systems we cite for instance [15–19].

2.3 Hydrogen production

As mention above the electricity generated by the wind turbine can be used to drive the water electrolysis process, which is achieved by the mean of an electrolyzer. Currently, the Proton Exchange Membrane (PEM) is one of the most developed and used technology [20]. This due to PEM long life cycle, high efficiency and it compatibility with the fluctuation of electricity generation from intermittent sources such is the case for wind energy [2].

The hydrogen production is directly related to amount of electricity generated and it can be estimated with the following formula [2,11,19]:

$$M_{H_2} = \frac{E \times \eta_{ele}}{HHV_{H_2}}$$

$M_{H_2}$ (Kg) is the amount of hydrogen produced; $E$ (kWh) is the electricity production from the wind turbine; $\eta_{ele}$ is the electrolyzer efficiency (75%); $HHV_{H_2}$ is the hydrogen higher heating value (39.4 kWh/kg).

2.4 Economic analysis

In order to quantify the cost of electricity and hydrogen production, the levelized cost of production metric is used in this study. This metric is widely used for the economic assessment of renewable energy projects and it’s computed from the technical and economic input of the energy system. In addition, it is very helpful when conduction a techno-economic investigation or for comparison of renewable energy systems between different locations.

The levelized cost of electricity $LCOE$ ($/kWh$) is define as follow [2,21]:

$$LCOE = \frac{C_{tot}}{E_{tot}}$$

$C_{tot}$ is the total cost of the system; $E_{tot}$ is the total electricity production.
\[
\begin{align*}
LCOE &= \frac{\sum_{i=0}^{N} \left( C_E \left(1 + T\right)^{-i} \right)}{\sum_{i=0}^{N} \left( E_i \left(1 + T\right)^{-i} \right)} \\
&= \frac{\sum_{i=0}^{N} \left( C_E \left(1 + T\right)^{-i} \right)}{\sum_{i=0}^{N} \left( E_i \left(1 + T\right)^{-i} \right)} \\
\end{align*}
\]
(Equation 2)

\(E_i\) (kWh/year) is the electricity production from the wind turbine in the year \(i\). \(N\) and \(T\) are the project lifetime and the discount rate taken as 20 years and 6% respectively. \(C_E\) ($) represents the investment cost of the wind turbine and it’s calculated by equation 3:

\[
C_E = C_{wt} + C_{in} + C_{O&M}
\]
(Equation 3)

\(C_{wt}\) is the cost of the wind turbine considered as 1150 $/kWp, \(C_{in}\) is the installation cost which represent 20% of the wind turbine cost, while \(C_{O&M}\) is the maintenance & operation cost and it represent 25% of the turbine cost [22–24].

Regarding the levelized cost of hydrogen \(LCO_{H_2}\) ($/Kg), its expressed by equation 4:

\[
LCO_{H_2} = \frac{\sum_{i=0}^{N} \left( \left( C_E + C_{elec} \right) \left(1 + T\right)^{-i} \right)}{\sum_{i=0}^{N} \left( M_{H_2,i} \left(1 + T\right)^{-i} \right)}
\]
(Equation 4)

\(M_{H_2,i}\) (Kg/year) is the hydrogen production in the year \(i\), \(C_{elec}\) ($) is the electrolyzer investment cost, which is given by equation 5:

\[
C_{elec} = C_{el} + C_{O&M} + C_{rep}
\]
(Equation 5)

\(C_{el}\) represent the capital cost of the electrolyzer and its calculated by the following formula [25]:

\[
C_{el} = C_{el,u} \times \left( \frac{M_{H_2} K_{el,th}}{8760 \eta_{el}} \right)
\]
(Equation 6)

\(C_{el,u}\) is the unit price of the electrolyzer (368 $/kWe), \(K_{el,th}\) (52.5 kWh/Kg) is the theoretical energy required by the electrolyzer and \(\eta_{el}\) is the electrolyzer efficiency. The operation & maintenance (\(C_{O&M}\)) and replacement (\(C_{rep}\)) cost are taken to be 2% and 25% respectively [2,25–27].

3. Results and discussion

3.1 Wind resources assessment

For wind energy based projects, the knowledge of the wind speed and direction frequencies are an important step toward evaluating the wind resource availability in a specific site. This due to the frequent changes in the wind direction caused by geographical effects and atmosphere circulation [6].
One of the most used methods for the assessment of wind resources is the wind rose diagram, because it provides both the wind direction and speed frequencies in a single polar diagram. The wind rose of Casablanca is presented in figure 1.

As it can be seen from the wind rose, the most dominant wind direction is the west both west-north and west-south, also the north-east direction is observed with a relatively high frequency. As for the wind speed the most frequent values are in the range of 3-5 m/s, however for a better understanding of the wind speed variation we plotted the hourly wind speed frequency through the year at 10 m and at the hub height (135 m) in figure 2 and 3 respectively.

Figure 1. Casablanca wind rose.

Figure 2. Wind speed frequency at 10 m.
Figure 3. Wind speed frequency at hub height (134 m).

The first observation is that high wind velocity is more frequent at 134 m, which were expected since the wind speed increase with higher altitude. For the 10 m, the most frequent wind speed is between 2 m/s and 3 m/s, while for the hub height the most frequent is in the range of 3-4 m/s, however, wind speed that are in the range of 4-5 m/s and 6-8 m/s are frequent as well.

In what follow, we will present the simulation results for the electricity and hydrogen production in different time steps.

3.2 Electricity production

The daily electricity production from the simulated wind turbine is presented in figure 4.

As it can be seen from figure 4, the electricity production varies greatly through the year, which is due to the high fluctuation of the wind speed. Indeed, the daily electricity generation ranges between 0 and 1638 MWh. The value 0 means that, in that day the minimal wind speed required by the wind turbine to start operating (Cut-in speed) was not reached. As for the highest value, it was recorded on March 15 where the daily average wind speed was 7 m/s at 10 m, which correspond to 11 m/s at hub height. However, due the low frequency of high wind speed (see figures 2 and3), the electricity production does not exceed 100 MWh in most days; in fact, the daily average electricity production is 80 MWh.

Regarding the monthly electricity production, it's plotted in figure 5. The amounts of electricity generated also differ from one month to another. The highest amount is observed in July with 3814 MWh and the lowest in January with 570 MWh while the monthly average electricity production is
2430 MWh. As for the annual electricity production the wind turbine produces 29.16 GWh and the LCOE is 0.24 $/kWh.

![Figure 5. Monthly electricity production.](image)

### 3.3 Hydrogen production

The hydrogen production is directly proportional to the electricity production and therefore, it follows the same pattern as it can be notice in figures 6 and 7. The simulated wind turbine if coupled with a PEM electrolyzer can generate a daily amount of hydrogen in the range of 0 and 31.8 Tons with a daily average of 1.52 Tons. Also, the monthly hydrogen production between 10.52 Tons and 70.42 Tons, while the monthly average 46.25 Tons. Regarding the total hydrogen production, the simulated system can generate 555 Tons annually with an $LCOE_{H_2}$ equal to 13.52 $/Kg.

![Figure 6. Daily hydrogen production.](image)
4. Conclusion

In this paper, a techno-economic simulation of electricity and hydrogen production from 4.2 MWp wind turbine under the climate of Casablanca, Morocco. For this reason, we used Greenius simulation tool to simulate the electricity production, then the simulation outputs were used to estimate the hydrogen production from a wind turbine/PEM electrolyzer system.

The results show that, the most dominant wind direction is the west and the most frequent wind speed at 10 m in the range of 3-5 m/s. As for electricity production the wind turbine can generate 29.16 GWh/year with an \( LCOE \) of 0.24 $/kWh. In addition, if coupled with an electrolyzer the wind turbine can produce 555 Tons of hydrogen annually with an \( LCO_H \) equal to 13.52 $/Kg.

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