21th International Conference on Renewable Energies and Power Quality (ICREPQ'23)
Madrid (Spain), 24th to 26th May 2023
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.21, July 2023

Utility-scale renewable hydrogen generation by wind turbines

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Abstract. In this paper, we use MHOGA software for the evaluation of a hydrogen generation system powered by wind turbines. We study the state of the art of the electrolyzers, obtaining the most important characteristics and costs of PEM electrolyzers. The optimization of a Wind-H2 system is performed, obtaining the best combination of components (wind turbines and electrolyzer) and control strategy for the hydrogen production. We will compare to the Wind-only system (wind farm which injects all the electricity produced to the gird). Two cases have been evaluated regarding the electricity price: Spanish SPOT price of 2019 and of 2021, with an expected increase of 1% annual. The Wind-H2 system can be competitive to the Wind-only system if the hydrogen sale price is 4.8 €/kg for the case of 2019 SPOT prices and 6.7 €/kg for the case of 2021 SPOT prices, considering 1% annual increase in the SPOT prices and 2% for the hydrogen price.

Key words. Wind, electrolyzer, hydrogen, utility-scale, price arbitrage, SPOT price.

1. Introduction

Hydrogen is a flexible and potentially zero-carbon emission energy carrier (if obtained by electrolysis powered by renewable energy) [1]. However, green hydrogen generation (by electrolysis using renewable power) was only 0.03% in 2020. [2].

It is clear that the ecological transition needs a high amount of green hydrogen, mainly generated by wind or PV. The electrolyzer uses DC electricity for the water electrolysis, obtaining hydrogen (the objective) and also oxygen. Hydrogen is stored and can be transported to the final users (fuel cell vehicles, etc.). Alkaline or PEM (proton exchange membrane) electrolyzers are the most mature technologies.

For 2030, the estimated cost of green hydrogen generation via electrolysis powered by wind and solar technologies is between 2.3 and 4.3/kgH2; prices of 5 €/kg can be competitive in 2030 for PEM electrolyzers powered by off-shore wind farms [3].

Wind farms sell electricity to the AC grid in the long term market through a power purchase agreement (PPA) or in the Daily / intraday market establishing the marginal cost of electricity (SPOT price, representing the cost of supplying an additional MWh to the grid) [4]. In this work, an electrolyzer will be added to the wind farm in order to generate hydrogen (and sell it) when the electricity price is low, trying to maximize the total benefits (selling electricity to the grid and selling hydrogen produced) and therefore the net present value (NPV) of the system. The Wind-H2 system will be compared to the Wind-only system. Several values of price of selling hydrogen will be considered.

2. System description

A wind farm composed of 4 wind turbines of 2 MW (total 8 MW) is considered in this work. The maximum power allowed to be injected to the grid is 6 MW. There is no load consumption and the benefits are obtained by selling electricity to the AC grid. An electrolyzer (which nominal power will be optimized) will be added in the system to generate hydrogen depending on the hourly electricity price (Fig. 1), trying to maximize benefits of selling electricity and hydrogen, obtaining the optimal system (maximizing the net present value, NPV).

Wind-only systems inject all the electricity to the AC grid at the time when it is being generated.

On the other hand, Wind-H2 systems can inject electricity or generate hydrogen depending on the electricity price: during hours with low electricity prices, the priority is to generate hydrogen (if power from the wind turbines is higher than the electrolyzer minimum power) and during hours with high electricity prices the priority is to inject the power generated by the wind turbines to the AC grid. Also, even if the priority is to inject power to the AC grid, if the wind turbines power is higher than the maximum power that can be injected to the AC grid, hydrogen is generated by the surplus power.

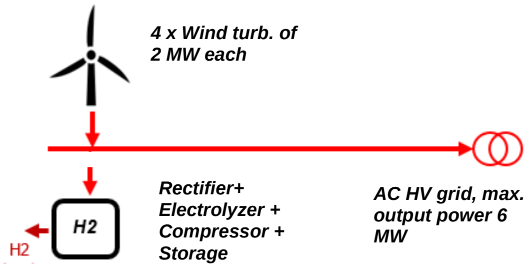

Fig. 1. PV-H2 system

The simulation and optimization of the system will be performed by MHOGA software (MegaWatt Hybrid Optimization by Genetic Algorithms) [5].

A. Location and wind speed

The system will be located near Zaragoza, Spain (latitude 41.86º N, longitude 1.08º W). The wind speed and temperature hourly data during one year can be directly downloaded by the software from different databases. In this case we will use the Renewable Ninja [6] database, downloading hourly data for the year 2019 for 100 m height (the hub height of the wind turbines), Figs. 2-4.
Fig. 2 shows the probability density function (PDF) of the wind speed (data, red curve), with an approximate Weibull form factor of 2.9 (green fit curve). Fig. 3 shows the hourly wind speed during the year while Fig. 4 shows the detail of several days (6 consecutive days in June).

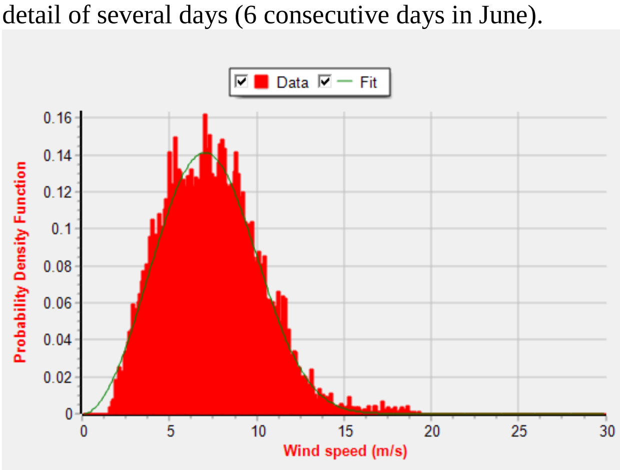

Fig. 2. Wind speed data PDF (red) and Weibull PDF which best fits the data (green, form factor 2.9).

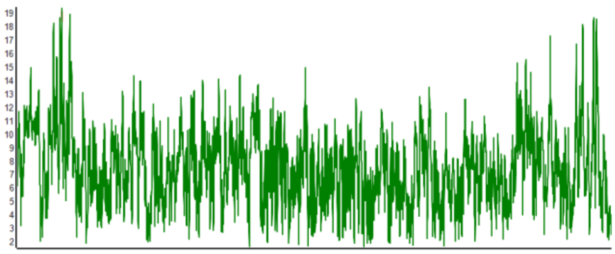

Fig. 3. Hourly wind speed (m/s) during the whole year.

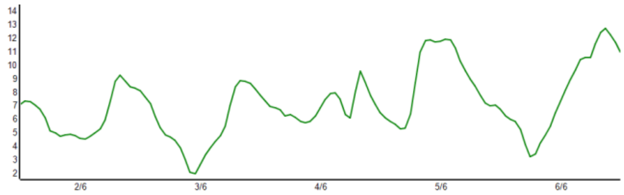

Fig. 4. Hourly wind speed for 6 consecutive days in June.

The average wind speed is 7.41 m/s, with an average monthly maximum of 9.63 m/s in January and minimum of 6.55 in July.
The location height is 247 m above the sea level. Fig. 5 shows the hourly temperature (ºC) for the whole year.

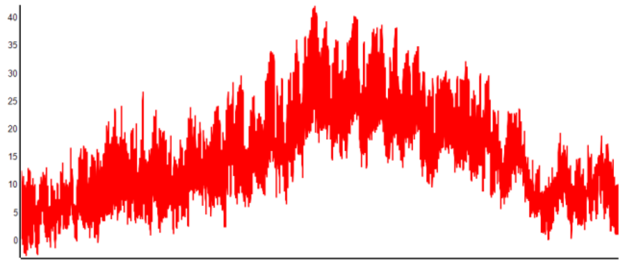

Fig. 5. Hourly temperature (ºC) for the whole year.

B. Components of the system

1) Wind farm:

The wind farm consists of 4 wind turbines of 2 MW nominal power each, pitch controlled. Fig. 6 shows the output power curve vs wind speed (red curve in standard conditions, green curve converted to the height of the location). During the simulation, for each time step the real density is obtained (considering the height above sea level and temperature), converting the power curve to the real density of each time step.

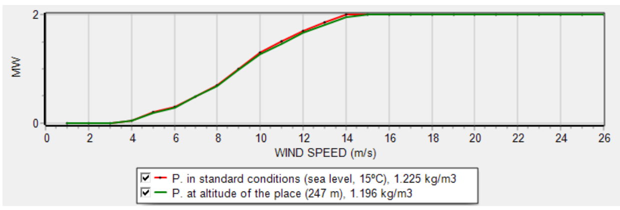

Fig. 6. Wind speed output power curve.

The CAPEX of each wind turbine is 2 MW, with a lifespan of 20 years and a replacement cost of 1.6 M€. Other CAPEX costs of the wind farm are assumed to be 20% of the wind turbines CAPEX. Annual OPEX of the wind farm is 2% of CAPEX.

2) Hydrogen system

They hydrogen system is composed of a rectifier (converts AC power to DC power), an electrolyzer (generates hydrogen, in this case at 30 bar), a compressor (increases pressure, in this case to 250 bar) and high pressure storage tanks (stores hydrogen at high pressure, ready to be delivered and sold).

Rectifier: an efficiency of 90% is considered for the rectifier, which cost will be included in the electrolyzer one.
Electrolyzer: PEM electrolyzers have better dynamic behaviour than alkaline ones, this feature make PEM better to be used in wind farms, due to the wind power intermittency and quick variability.
We will consider 5 different cases, between 1 and 5 MW rated power, with a CAPEX of 1691 €/kW [1] (assuming 1€=1$). Efficiency for nominal conditions is 54.3 kWh/kg (61.4% on a lower heating value (LHV) basis, 72.5% on a higher heating value (HHV)) [1]. The DC electrical power consumption during time t, P(t) (kW) is modelled as follows:

$$P(t) = A \cdot Q(t) + B \cdot Q_n \qquad (1)$$

where Q(t) is the hydrogen output mass flow (kg/h) during time t, Q_n is the nominal hydrogen mass flow (kg/h), A and B are the consumption parameters (kW/kg/h), in our case A = 44.3 kWh/kg and B = 10 kWh/kg (for nominal conditions, $P=(A+B)\cdot Q_n=54.3\cdot Q_n$). Fig. 6 shows the DC electrical consumption (red, left axis) and efficiency (% of HHV, green, right axis) vs output mass flow for the case of 1 MW electrolyzer.

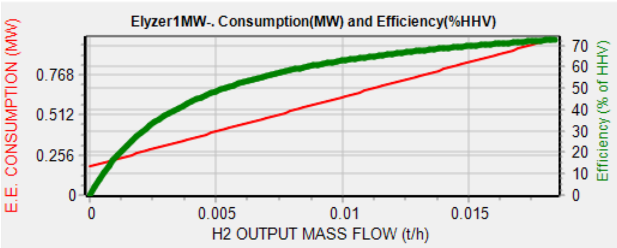

Fig. 6. Power consumption and efficiency vs output mass flow, electrolyzer of 1 MW rated power.

OPEX is assumed to be 3% of CAPEX /yr [7] (50.73 €/kW/year, which, supposing about 6,000 hours of operation per year, it will be about 0.008 €/kW/h of operation), and the cost of stack replacement 30% of CAPEX, being the lifetime for stack replacement 80,000 h of operation. Minimum partial load is 10% and hot-standby consumption 2% [7].
Regarding the water consumption, cost of water is assumed to be 3.8 €/m^3 and the consumption of water to produce hydrogen is 15 L/kg [7], therefore a cost of 0.057 €/kg of H2 produced will be considered for water consumption, which is almost negligible compared to the typical hydrogen selling prices of several € per kg.
Compressor: a hydraulic compressor with CAPEX of 5,000 €/kg/h of nominal hydrogen flow has been considered, with an electrical consumption of 2 kWh/kg of H2 compressed [7] and an annual OPEX of 3% of CAPEX. Considering the electrolyzer consumption, the compressor CAPEX will be 5,000 €/kg/h / (54.3kWh/kg) = 92 €/kW of electrolyzer nominal power.
Storage: tanks at 250 bar are considered, with a CAPEX of 400 €/kg of hydrogen storage capacity [7]. A storage capacity of 1,000 kg per MW of electrolyzer rated power will be considered (that is, 1 kg/kW), therefore the storage cost per kW of electrolyzer rated power is 400 €/kW. Annual OPEX of 3% of CAPEX is considered.

Total CAPEX and total OPEX:
The total CAPEX (rectifier + electrolyzer + compressor + storage) per kW of electrolyzer rated power will be: 1691 €/kW (rectifier + electrolzyer) + 92 €/kW (compressor) + 400 €/kW (storage) = 2,183 €/kW.
The total annual OPEX (rectifier + electrolyzer + compressor + storage) per kW of electrolyzer rated power will be: 3% of total CAPEX: 3/100·2183 = 65.5 €/kW/yr. Considering 6,000 hours of electrolyzer operation per year, this will be about 11 €/h of operation.
Other CAPEX costs of the hydrogen system are assumed to be 20% of the total CAPEX (engineering + control station + interconnexion and commissioning) [7].
In order to calculate the replacement cost of the stack, it will be assumed that this cost will be reduced 10% annually, with a limit of reduction of 60% (assuming that then it becomes a mature technology, increasing since then with general inflation, which is 2% annual).

C. Financial costs and sell electricity price

Financial costs considered are the following: nominal discount rate 7%, general inflation rate 2%. Project lifespan considered is 20 years (as wind turbines lifespan), and a loan of 100% of CAPEX is considered, with a 4% of interest rate during 10 years.
The electricity SPOT prices of 2019 and of 2021 in Spain (Spanish electricity system operator [8]) have been considered for the selling electricity price, Fig. 7 and 8. A 1% annual increase will be considered during the 20 years of the system lifetime.

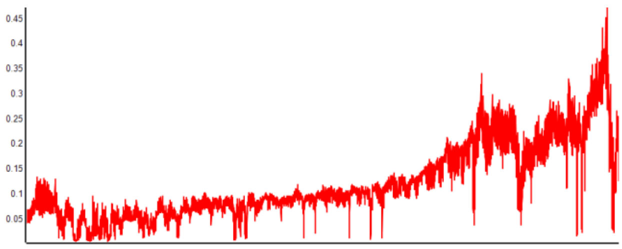

Fig. 7. SPOT price, Spain, year 2019

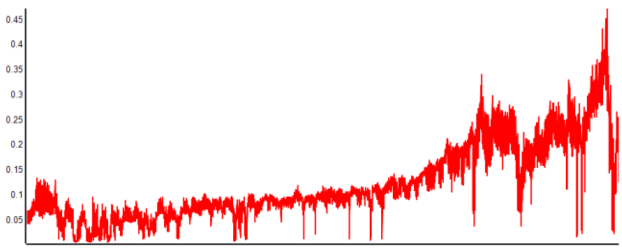

Fig. 8. SPOT price, Spain, year 2021

A power of 0.1 MW will be contracted for buying electricity to the AC grid (with a fixed annual cost of 40 €/kW) needed when there is no wind generation and the electrolyzer is in stand-by mode (consuming 2% of its rated power).

2. Management strategy

An electricity selling price setpoint X (€/kWh) will be optimized.

- During a time step t, if the electricity price is higher than X, the priority will be to inject electricity from the wind farm to the AC grid.
- During a time step t, if the electricity price is lower than X, the priority will be to generate hydrogen with the electricity generated by the wind farm.

X value is for the first year of the simulation, next years (up to the system lifetime) X will be increased in the same 1% annual as the SPOT electricity price.

3. System optimization

Each combination of components (wind farm and electrolyzer with its auxiliary components of 1, 2, 3, 4 or 5 MW) and management strategy (10 different values from minimum to maximum annual electricity price) will be evaluated, simulating each of them in 1 hour time steps during a typical year (the software can also simulate in time steps up to 1-minute and also it can simulate the performance of the system during all the years of the system lifetime).

The net present value (NPV) will be calculated for each combination and management strategy, accounting all the incomes for the energy selling and costs (including CAPEX, OPEX for the different years, components replacement during the system lifetime and residual value of the components at the end of the system lifetime), converting all the incomes and costs to the initial time of the inversion. After evaluating all the combinations, they are sorted from best to worst NPV. Also other economical parameters are calculated, as internal rate of return (IRR), capacity factor, levelized cost of energy (LCOE), etc.

4. Results

A) Hydrogen sell price of 2.3 €/kg with inflation of 2%.

First, a hydrogen sell price of 2.3 €/kg, with 2% annual increase have been considered.

Two cases have been optimized:

- Using 2019 SPOT electricity price, annual inflation 1%
- Using 2021 SPOT electricity price, annual inflation 1%

For each case, the optimization has been carried out, evaluating all the possible combinations of components.

The Wind-only system and the optimal Wind-H2 system (system with maximum NPV) obtained for each case are shown in Table I.

We can see that for both cases, Wind-only system has better NPV than the optimal Wind-H2 system, concluding that, for the price of 2.3 €/kgH2 (with 2% annual increase), it is not worth to generate hydrogen.

Each system is simulated during a whole year, but, in order to show the performance of the system, in Fig. 9 we can see the simulation of 3 consecutive days for the optimal PV-H2 system for 2019 SPOT prices.

We can see that in the first and last days (9th and 11th February) the electricity price of the day is higher than X = 0.033 €/kWh, therefore the electrolyzer will not work during these days (unless there was surplus power form the wind turbines which could not be injected to the grid). The second day (10th February) there are some hours when price is lower than X, therefore in these hours the priority is to power the electrolyzer and hydrogen is generated. As the electrolyzer rated power is 1 MW, the surplus power is injected to the gird. Electricity sold to the grid is shown in purple colour in the lower graph, while wind generation is shown in green and electrolyzer AC power consumption in turquoise dotted line.

Table I. – Optimal system for 2019 and 2021 SPOT prices, hydrogen price 2.3 €/kg, inflation 2% annual.

	2019 SPOT		2021 SPOT	
	Wind-only	Wind-H2	Wind-only	Wind-H2
Wind farm (MW)	8	8	8	8
Electrolyzer (MW)	-	1	-	1
X (€/kWh)	-	0.033	-	0.0045
NPV (M€)	1.59	-0.60	19.56	17.20
Investment cost (M€)	9.6	12.22	9.6	12.22
IRR (%)	7.4	0	26.22	20.37
Capacity factor (%)	32.08	32.02	32.08	32.3
LCOE (€/kWh)	0.037	0.045	0.037	0.045
Wind gen. (GWh/yr)	23.22	23.22	23.22	23.22
Electrolyzer consumption (GWh/yr)	-	1.15	-	0.665
Hours of electrolyzer operation per year	0	1,188	-	686
Sell electricity (GWh/yr)	22.48	21.77	22.48	22.31
Sell hydrogen (t/yr)	-	16.9	-	8.14
Sell electricity incomes, 1st year (M€)	1.04	1.02	2.60	2.58
Sell hydrogen incomes, 1st year (M€)	-	0.039	-	0.019
Sell electricity incomes, NPV (M€)	11.98	11.74	29.96	29.73
Sell hydrogen incomes, NPV (M€)	-	0.488	-	0.235
Wind farm cost, NPC (M€)	10.01	10.01	10.01	10.01
Hydrogen cost (electrolyzer and auxliariy), NPC (M€)	-	2.347	-	2.278

Fig. 10 and 11 show the annual simulation of the optimal Wind-H2 system of 2019 SPOT prices. In Fig. 10 the purchased energy is for the hours when there is no wind generation but the electrolyzer is in stand-by mode (consumes 2% of its rated power). The lower graph of Fig. 11 shows the cumulated hydrogen generated by the electrolyzer (last value is the hydrogen sold during the whole year), in HHV values (MWh). The hydrogen sold during the year is 16.9 t (Table I), which converted to

HHV value (39.4 MWh/t) equals 16.9 t · 39.4 MWh/t = 665.8 MWh.

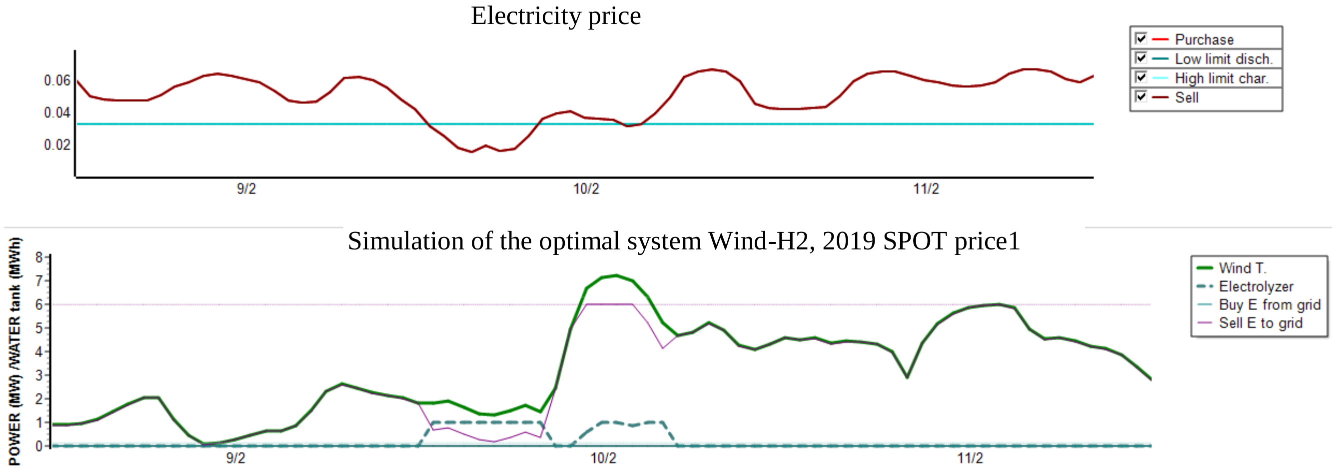

Fig. 9. Electricity price with X setpoint (upper graph) and simulation of the optimal Wind-H2 system for 2019 SPOT prices during three consecutive days (9^{th} to 11^{th} February).

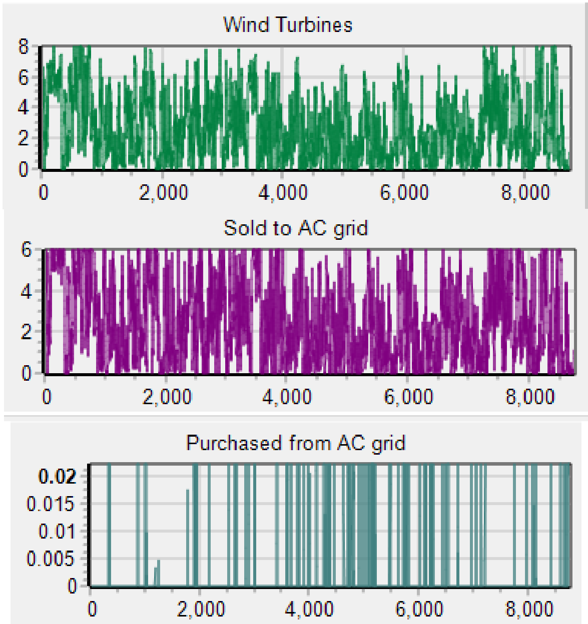

Fig. 10. Horly wind generation, energy injected to the grid and energy purchased from the grid during a full year (MW), optimal Wind-H2 system for 2019 SPOT prices.

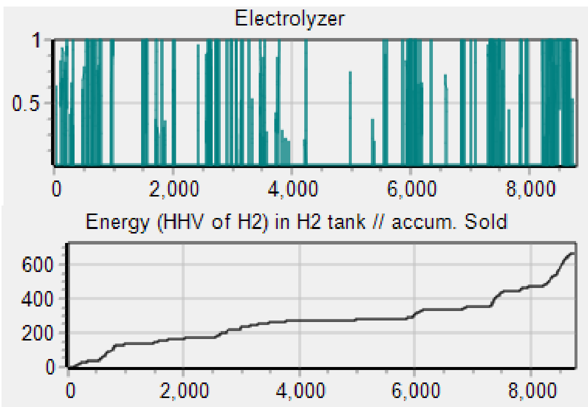

Fig. 11. Hourly power consumed by the electrolyzer (MW) and cummulated hydroen generated, in HHV values (MWh) during a full year, optimal Wind-H2 system for 2019 SPOT prices

B) Different hydrogen sell prices.

For both 2019 and 2021 SPOT prices, we have changed the hydrogen selling price to 4 and 5 €/kg with annual inflation 2%, obtaining the results of Table II.

Table II. – Optimal system for 2019 and 2021 SPOT prices

	2019 SPOT		2021 SPOT	
	4 €/kg	5 €/kg	4 €/kg	5 €/kg
Wind farm (MW)	8	8	8	8
Electrolyzer (MW)	1	1	1	1
X (€/kWh)	0.066	0.082	0.0045	0.1103
NPV (M€)	0.377	1.901	17.373	17.78

For 2019 SPOT prices, with 5 €/kg the NPV of the Wind-H2 system is higher than the NPV of the Wind-only system, therefore with this price it would be worth to generate hydrogen during the hours indicated by the strategy (when electricity price is lower than 0.082 €/kWh). However, for 2021 SPOT prices, even for 5 €/kg the NPV of the Wind-H2 system is lower than the Wind-only system one.

C) Hydrogen sell prices needed to equal the NPV of the Wind-only system.

The hydrogen price which equals the NPV of the Wind-H2 system to the NPV of the Wind-only system is 4.8 €/kg for the case of 2019 SPOT prices and 6.7 €/kg for the case of 2021 SPOT prices. If the electricity price is higher, the hydrogen price must be higher to be competitive the Wind-H2 system with the Wind-only system.

5. Conclusion

In this paper, we have used MHOGA software for the evaluation of the economical viability of the Wind-H2 systems. Two cases have been considered: Spanish SPOT price of 2019 and of 2021, both with an expected increase of 1% annual. The hydrogen price in order to equal the NPV of the Wind-H2 system to the NPV of the Wind-only system is 4.8 €/kg for the case of 2019 SPOT prices and 6.7 €/kg for the case of 2021 SPOT prices, considering 1% annual increase in the SPOT prices and 2% for the hydrogen price. Both values are obtained for the optimal system management.

Acknowledgement

This publication is part of the project PID2021-123172OB-I00 funded by MCIN/AEI/10.13039/501100011033/FEDER, UE.

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