Renewable Energy, Environment, and Power Quality Journal (REE&PQJ)
ISSN:3020-531X
Volume No.2, July 2024

Stable hydrogen generation by wind power, grid and battery

Rodolfo Dufo-López[1], Juan M. Lujano-Rojas[1], José L. Bernal-Agustín[1], Jesús S. Artal-Sevil[1], Ángel A. Bayod-Rújula[1].
[1] Department of Electrical Engineering
E.I.N.A., Zaragoza University
C/María de Luna, 3, 50018 Zaragoza, Spain
Phone number:+0034876555124

Abstract. In this work, we study the stable generation of hydrogen by means of the electrolyzer fed by renewable sources, battery and grid. Due to the intermittent nature of the renewable sources (PV, wind), the hydrogen generation by the electrolyzer cannot be stable during the time except if there is another electricity source to fulfil the difference between the electrolyzer nominal power and the renewable power. The AC electrical grid will supply that difference during hours when the electricity price is low, while the batteries will supply the difference when the electricity price is high. Also, batteries will be charged by the grid when electricity price is low. We compare the performance and economical results with the case of using only the grid for supplying that difference. Considering a hypothetical electricity hourly price with 3% annual inflation, the system with battery has a levelized cost of hydrogen (LCOH) of 4.25 €/kg with the actual present battery CAPEX (200 €/kWh) while it has a LCOH of 3.95 €/kg if we consider a much lower future battery CAPEX of 20 €/kWh (10 times lower than nowadays). The system without battery has a LCOH of 4.14 €/kg.

Key words. Electrolyzer, hydrogen, renewable, wind, off-grid, daily operation, control strategy, optimization, genetic algorithms.

1. Introduction

Hydrogen obtained by water electrolysis is a flexible and potentially zero-carbon emission energy carrier, if the electrolyzer is supplied by renewable sources [1]. The main issue with the renewable sources is its intermittency, therefore the supply of the electrolyzer by means of PV and/or wind energy implies variation in electrolyzer input power [2]. These input power variations imply important maintenance issues in the electrolyzer, which can reduce its useful lifetime. To avoid these input power variations, the electrolyzer can run only during hours when renewable generation is higher than the electrolyzer rated power, or we can import power from the AC grid to supply the difference.

In this paper, we will consider not only the AC grid to supply the difference, but also batteries (which will be charged by the AC grid during low electricity price periods). Then, the electrolyzer will always run at full load, using the renewable power and, if necessary, the power from the grid (during hours at low electricity price) or from the batteries (during hours at high electricity price). Doing this, it is possible that the total cost of generating hydrogen is lower than in the case of using only the grid for the difference. Fig. 1 shows the scheme of the system, where we will consider only wind turbines for the renewable generation.
The results shown in this paper are obtained by using the software MHOGA [3], which author is the main author of this paper.

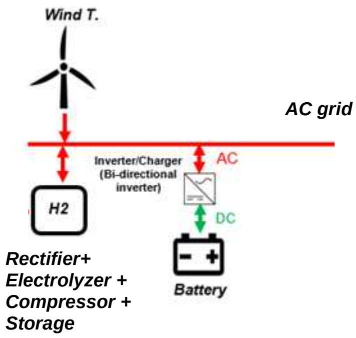

Fig. 1. Hydrogen generating system powered by wind turibes + grid + battery.

Previous studies on green hydrogen generation have obtained a wide variety of LCOH [1]. An extensive review of hydrogen production based on PV and wind turbines was presented by Benghanem *et al.* [4], reporting a levelized cost of hydrogen (LCOH) from 3.73 to 4.65 $/kg. Other authors studied the hydrogen generation by renewable sources in different countries. Mazzeo *et al.* [5] compared different hydrogen generating systems (PV–hydrogen, wind–hydrogen, and hybrid) in different cities. Park *et al.* [6] reported an LCOH of 5.9 $/kg. Pagani *et al.* [7] obtained LCOH from 5.30 to 6.03 €/kg H2. Müller *et al.* [8] obtained 3.7–9.9 €/kg. García and Oliva [9] obtained 2.09–3.28 $/kg.

2. Energy management

The energy management proposed in this paper is to run the electrolyzer at full load all the time: if the power from the renewable sources is not enough, the net electrolyzer load will be supplied from the electrical grid (purchased to the AC grid). But, if the grid electricity price is higher than a specific limit, the priority to supply the net electrolyzer load will be from the battery. If the power form the renewable sources is higher than the rated power of the electrolyzer, the surplus power will be sold to the AC grid.
Therefore:

- Periods of low electricity price (LEP): energy from the wind farm is used to feed the electrolyzer (which runs at full power) and charge the battery at the maximum charge rate allowed. If there is not enough power from the renewable sources, buy the rest to the grid.
- Periods of medium electricity price: energy from the wind farm is used to feed the electrolyzer (which runs at full power). If not enough, buy the rest to the grid.
- Periods of high electricity price (HEP): if the power from the renewable sources is not enough to run the electrolyzer at full load, the rest will be supplied by the battery; if not enough, buy the rest to the grid.

3. Case study

A system located near Zaragoza will be considered. The system is composed by 17 wind turbines of 4 MW rated power (output power curve in Fig. 2), an alkaline electrolyzer of 20 MW rated power (consumption and efficiency curves in Fig. 3) and a battery bank of 50 MWh (10 units of 5 MWh in parallel, Fig. 4 shows the cycles to failure and lifetime cycled energy of each unit). The inverter-charger of the battery is of 5 MW rated power, the inverter efficiency is shown in Fig. 5 and the rectifier efficiency is a fixed value of 98%. The electrolyzer efficiency has an efficiency of 95%.

The components CAPEX are 1€/W for the wind turbines (2% annual OPEX), electrolyzer 1.2 €/W (13.2 €/h/MW OPEX) [2] and inverter-charger 0.1 €/VA. For the batteries, a CAPEX of 200 €/kWh is considered for the actual present conditions. Also, a second case of much lower battery CAPEX will be considered, 10 times lower (it is supposed it will be achieved in some years): 20 €/kWh.

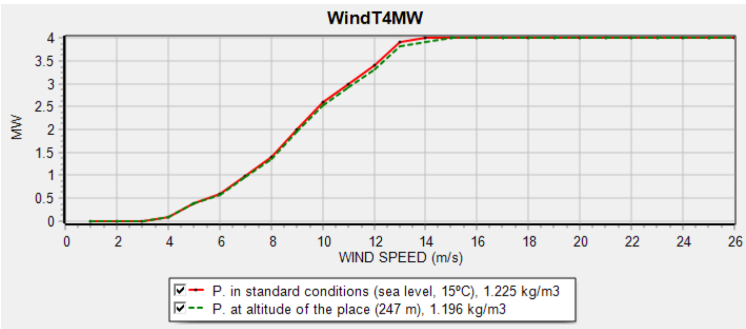

Fig. 2. Wind turbine output power curve (MW) vs wind speed (m/s).

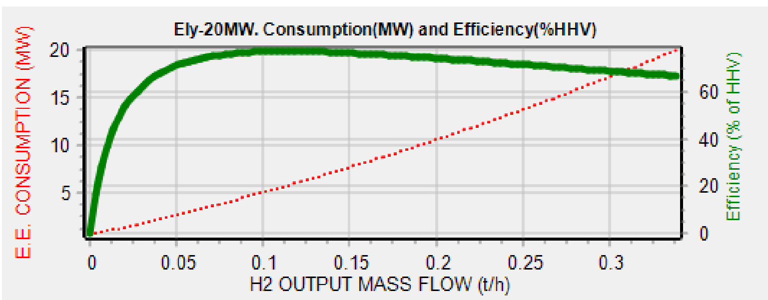

Fig. 3. Electrolyzer electrical consumption (MW, red, left axis) and efficiency (%, green, dots, right axis) vs H_2 output mass flow (t/h).

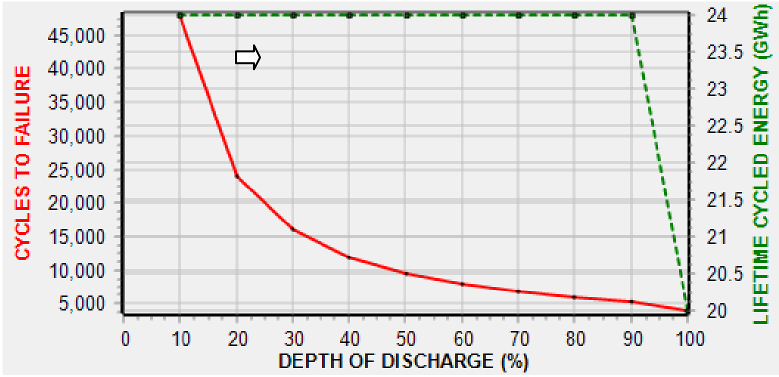

Fig. 4. Cycles to failure (red, left axis) and lifetime cycled energy (GWh, green, dash, right axis) vs depth of discharge, DOD (%). 5 MWh battery unit.

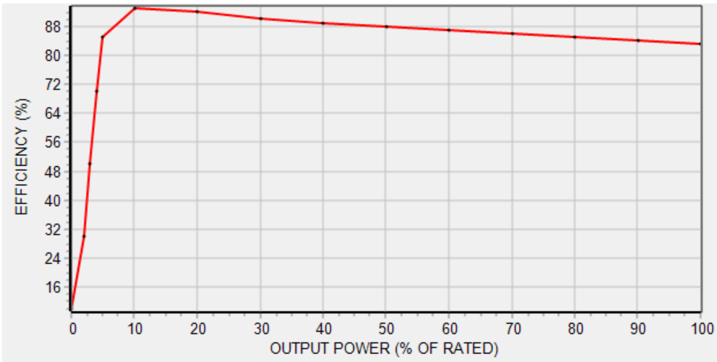

Fig. 5. Inverter-charger efficiency in inverter mode (%) vs. output power (% of rated).

Each year the hourly electricity price curve is different. In this case, we use a hypothetical hourly electricity purchase price (€/kWh) during the year, shown in Fig. 6 (detail for a specific day, January 30th). Average purchase electricity price is 0.06 €/kWh, while minimum and maximum values are 0.001 and 0.329 €/kWh. The selling price is supposed to be 80% of the purchase price (in the electrical market, selling price is lower than the purchasing price, due to charges). Annual inflation of 3% is considered.

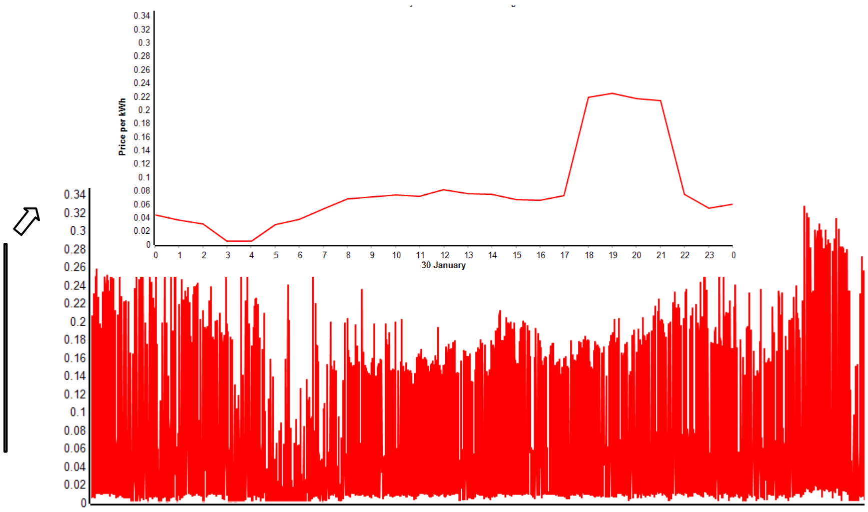

Fig. 6. Electricity purchase price during the year (€/kWh).

Considering the electricity price, we have fixed a value of LEP of 0.03 €/kWh (when electricity price is lower than this value, batteries will be charged form the grid and electrolyzer will get the power difference from the grid to run at full load) and HEP of 0.1 €/kWh (when electricity price is higher than this value, batteries will supply to the power difference to run at full load).

The simulation of the system is shown in Fig. 7, for a specific day (for example, January 19th). Upper graph shows the electricity price while lower graph shows the power of the different components (left axis) and state of charge (SOC) of the battery (right axis).

We can see that the electrolyzer (turquoise dotted curve) runs at rated power all the time, using the wind power (green curve) as the main source. When wind power is lower than 20 MW, it uses the grid power (turquoise thin curve) to get the difference (all the hours except from 19 to 20 h), unless the electricity price is higher than HEP (from 19 to 20 h), when batteries supply the difference (battery discharge blue curve).

Battery bank is charged (light maroon curve) when price is lower than LEP (from 3 a.m.) until they are fully charged. SOC is shown in right axis, red curve (limits in pink). Surplus energy which cannot be used by the system is sold to the grid (purple thin curve).

Fig. 8, shows the simulation of another 24 h, January 27-28th. During these 24 h, we can see battery is not charged or discharged, because renewable power during all the time (except at 9 am. day 28th) is higher than the rated power of the electrolyzer (20 MW). At 9 am. day 28th renewable power is lower than 20 MW, therefore the difference is obtained by the grid and battery is not charged, as the electricity price is between HEP and LEP.

Fig. 9 shows the power of the different components during the year, one by one. Fig. 10 shows the probability density functions (PDF) of the power during the year of the different components (energy in the case of energy in the battery bank). Also, below each graph, we can see the mean and standard deviation of the power or of the energy.
Fig. 11 shows the hydrogen detailed graphs: monthly hydrogen mass generated and energy consumed by the electrolyzer, in columns (in this case, as electrolzyer runs at full load during all the time, hydrogen production is stable, and the only differences from each month are due to the number of days of difference). Also, we can see the cumulated hydrogen generation in the black curve (at the end of the year, around 3,000 t of hydrogen are generated).
The levelized cost of hydrogen (LCOH) of the proposed system is 4.25 €/kg with the present actual battery CAPEX (200 €/kWh) while it is reduced to 3.95 €/kg if the battery CAPEX is supposed to be 10 times lower (20 €/kWh).
Using only grid for the energy difference (no battery bank, simulation in Fig. 12), the LCOH obtained was 4.14 €/kg.

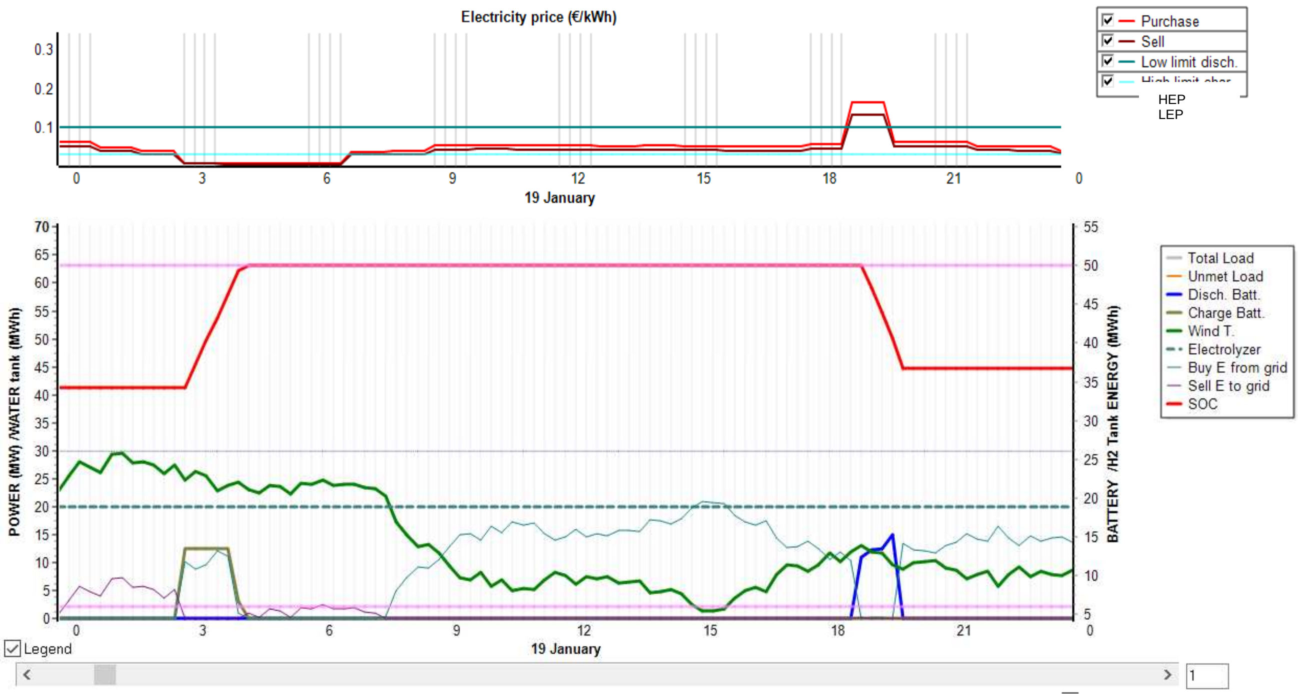

Fig. 7. Simulation of the system, shown January 19th. MHOGA software

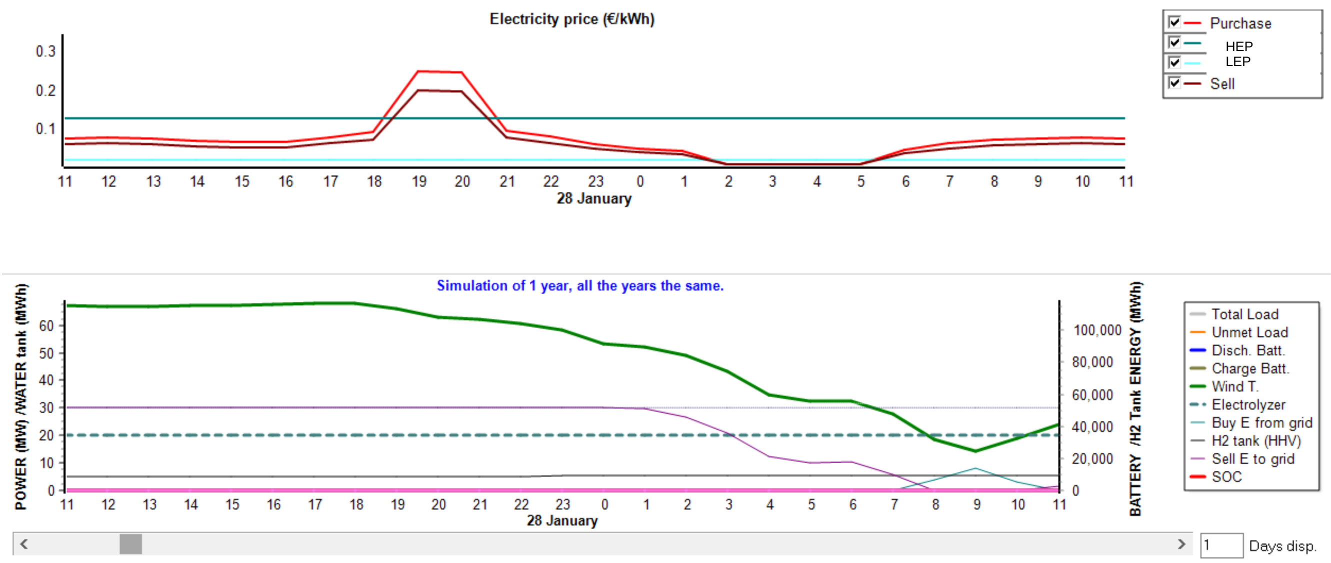

Fig. 8. Simulation of the system, shown January end of day 27th – first of day 28th. MHOGA software

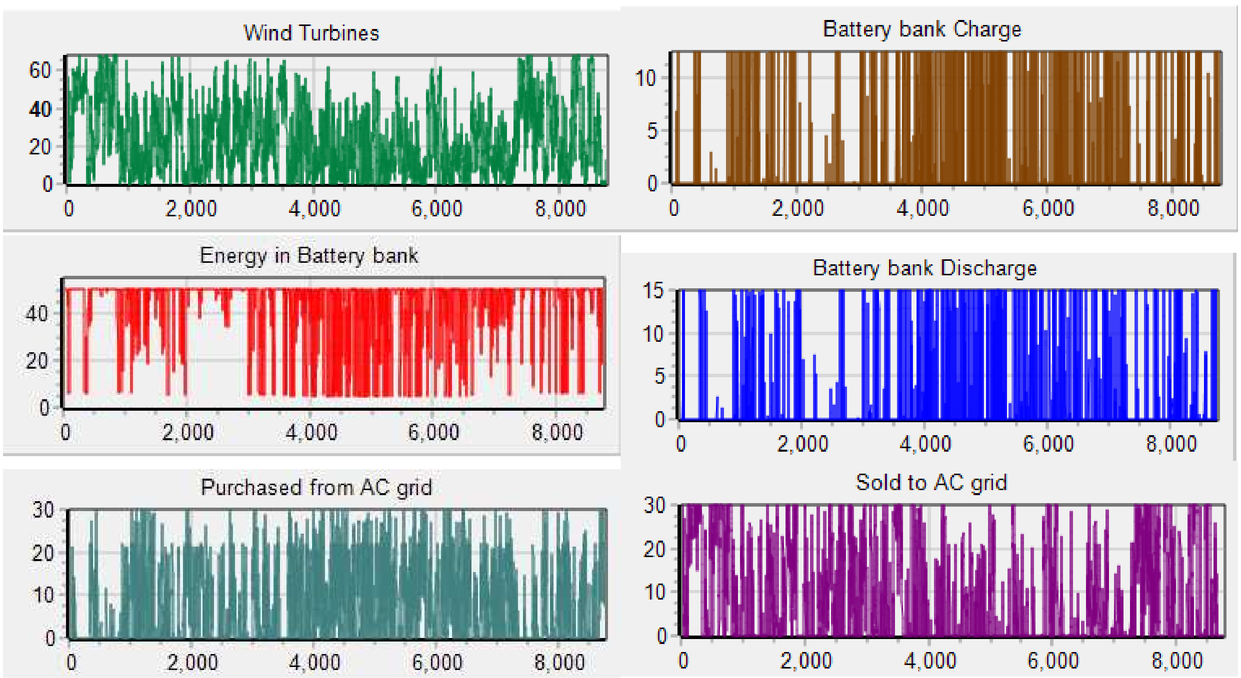

Fig. 9. Performance of the different components (hourly power or energy during the year), separated. MHOGA software.

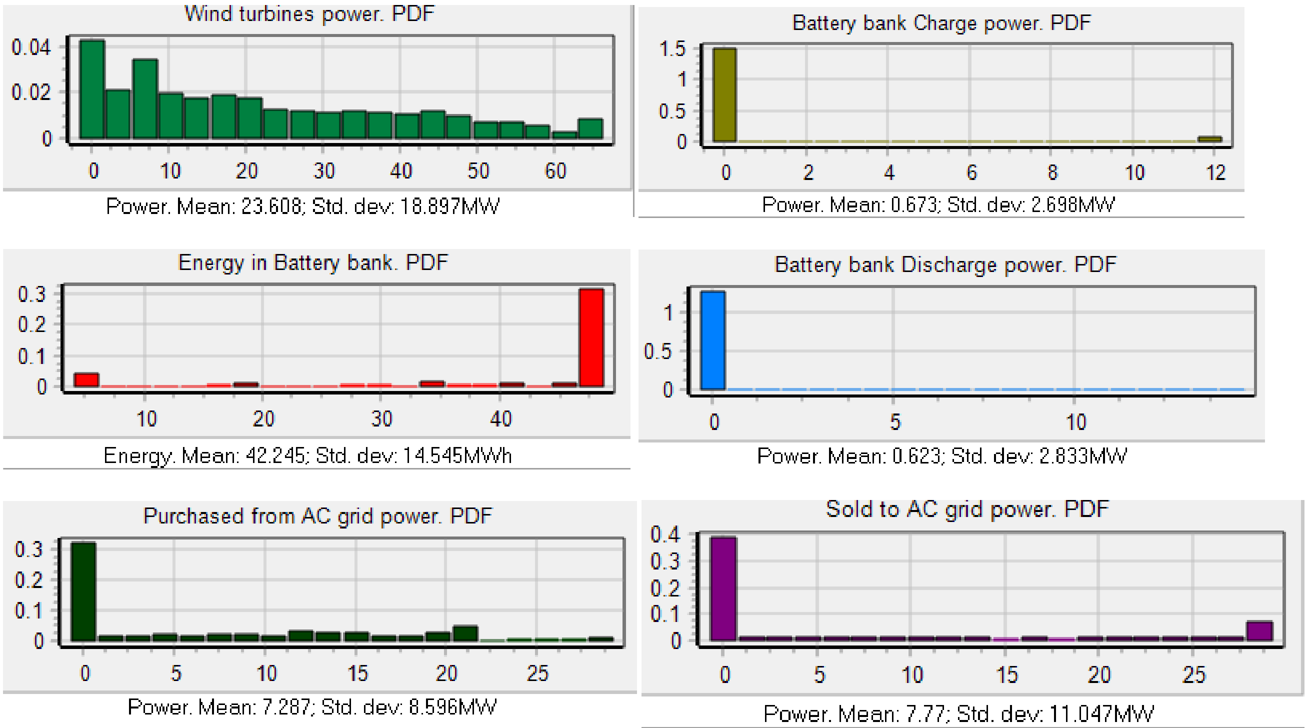

Fig. 10. PDF graphs, mean and standard deviation of the power / energy during the year of the different components. MHOGA software.

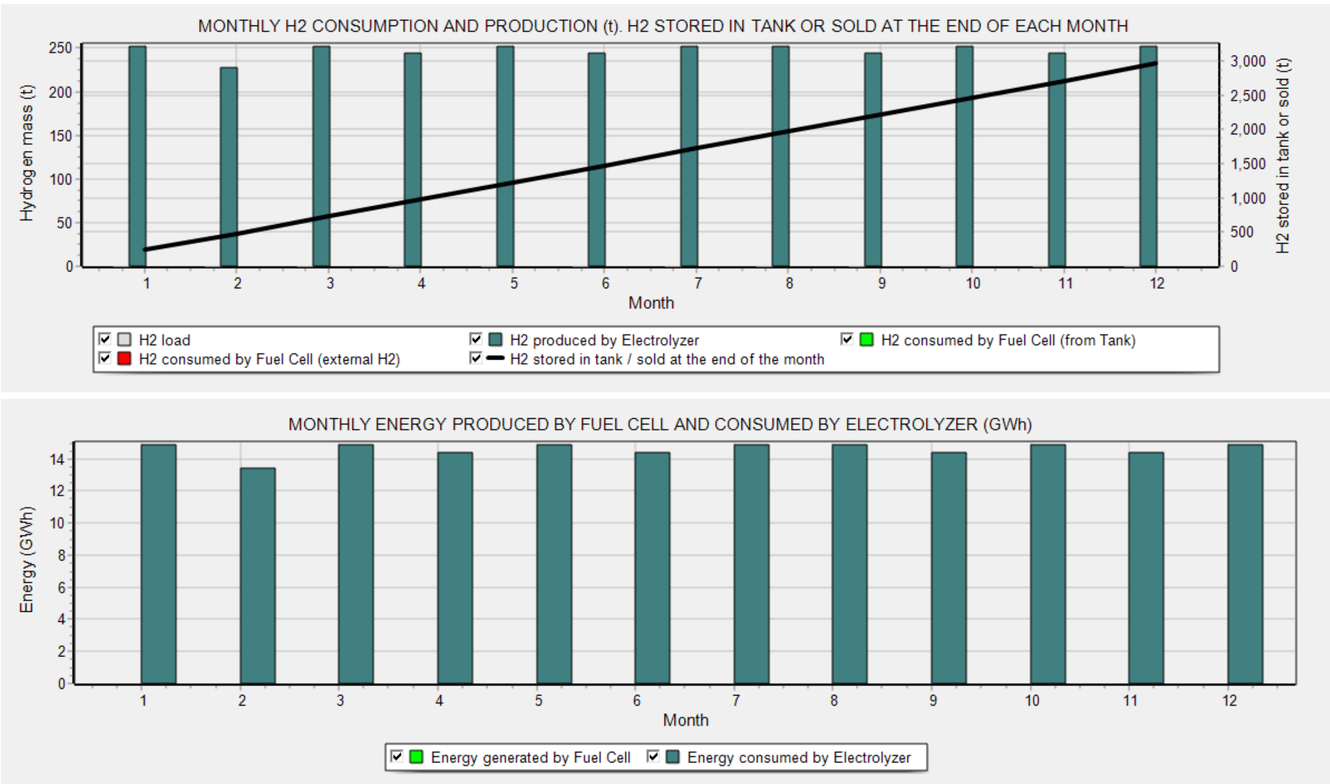

Fig. 11. Hydrogen results. MHOGA software.

Fig. 12. Simulation of the system without battery, shown January 19th. MHOGA software.

4. Conclusion

In this work, a case study of hydrogen generation by means of electrolyzer powered by wind turbines, grid and battery is shown. The electrolyzer must run at full load all the time, to avoid maintenance problems which would appear with intermittent operation (powered only by the wind turbines). The battery is charged during periods of low electricity price, and supplies the power needed to the electrolyzer (to run at full load) during the periods of high electricity price. The rest of the periods the grid is used to feed the electrolyzer with the difference power to run at full load. We have simulated the performance of the system, calculating all the related costs and incomes, obtaining the levelized cost of hydrogen of the system. A hypothetical hourly electricity price has been considered (as every year it is different), with an annual inflation of 3%; the average purchase electricity price is 0.06 €/kWh, while minimum and maximum values are 0.001 and 0.329 €/kWh and the selling price is supposed to be 80% of the purchase price. With this considerations, and using actual costs for the components, the levelized cost of hydrogen obtained is 4.25 €/kg for the system with battery, while considering the same system without battery the LCOH would be 4.14 €/kg. Considering the same system with battery but reducing battery CAPEX to 20 €/kWh (10 times lower than nowadays value), the LCOE would be 3.95 €/kg. The main conclusion is that, with present battery CAPEX and with the electricity price hourly curve considered, it is not worth to use batteries to feed the electrolyzer, it is better to use directly the grid. A high CAPEX reduction is needed for the batteries so that their use is justified in this kind of systems. Using different components CAPEX and electricity price, LCOH would be different, therefore future work should be done evaluating different cases.

Acknowledgement

Funding: This work was supported by the Spanish Government (Ministerio de Ciencia e Innovación, Agencia Estatal de Investigación) and by the European Regional Development Fund [Grant PID2021-123172OB-I00 funded by MCIN/AEI/ 10.13039/501100011033 and by “ERDF A way of making Europe”].

References

[1] M. Koleva, O.J. Guerra, J. Eichman, B.M. Hodge, J. Kurtz, Optimal design of solar-driven electrolytic hydrogen production systems within electricity markets, J. Power Sources. 483 (2021) 229183. https://doi.org/10.1016/j.jpowsour.2020.229183.

[2] R. Dufo-López, J.M. Lujano-Rojas, J.L. Bernal-Agustín, Optimisation of size and control strategy in utility-scale green hydrogen production systems, Int. J. Hydrogen Energy. 0 (2023). https://doi.org/10.1016/j.ijhydene.2023.08.273.

[3] R. Dufo-López, Software iHOGA / MHOGA, (2022). https://ihoga.unizar.es/en.

[4] M. Benghanem, A. Mellit, H. Almohamadi, S. Haddad, N. Chettibi, A.M. Alanazi, D. Dasalla, A. Alzahrani, Hydrogen Production Methods Based on Solar and Wind Energy: A Review, Energies. 16 (2023). https://doi.org/10.3390/en16020757.

[5] D. Mazzeo, M.S. Herdem, N. Matera, J.Z. Wen, Green hydrogen production: Analysis for different single or combined large-scale photovoltaic and wind renewable systems, Renew. Energy. 200 (2022) 360–378. https://doi.org/10.1016/j.renene.2022.09.057.

[6] J. Park, K. Hwan, C. Kim, W. Chul, M. Kim, J. Hun, H. Cho, J.H. Lee, Green hydrogen to tackle the power curtailment : Meteorological data-based capacity factor and techno-economic analysis, Appl. Energy. 340 (2023) 121016. https://doi.org/10.1016/j.apenergy.2023.121016.

[7] G. Pagani, Y. Hajimolana, C. Acar, Green hydrogen for ammonia production – A case for the Netherlands, Int. J. Hydrogen Energy. (2023). https://doi.org/10.1016/j.ijhydene.2023.06.309.

[8] L.A. Müller, A. Leonard, P.A. Trotter, S. Hirmer, Green hydrogen production and use in low- and middle-income countries: A

least-cost geospatial modelling approach applied to Kenya, Appl. Energy. 343 (2023) 121219. https://doi.org/10.1016/j.apenergy.2023.121219.
[9] M. Garcia G., S. Oliva H., Technical, economic, and CO2 emissions assessment of green hydrogen production from solar/wind energy: The case of Chile, Energy. 278 (2023) 127981. https://doi.org/10.1016/j.energy.2023.127981.