Techno-economic study of hydrogen production using PV, wind power and battery storage

V. Papadopoulos[1], J. Knockaert[1], C. Develder[2], J. Desmet[1]

[1] UGent, Faculty of Engineering and Architecture, EELAB/Lemcko, Belgium
[2] UGent - Imec, Department of Information Technology, IDLab, Belgium

Abstract—**Hydrogen is regarded by many scientists as the energy fuel of the future, provided that it is produced by non-polluting renewable energy systems (RES) such as photovoltaics and wind turbines. The majority of studies focusing on hydrogen production with RES have shown that such installations are not yet feasible, at least from an economic perspective, primarily due to significant capital expenditures. Conversely, in this paper, we show that the hydrogen technology can already deliver some interesting investment opportunities. In the present paper, we address a system comprising a 15 MW PV park, wind power, battery storage and a 1 MW PEM electrolyzer. Our study comprises two parts. (i) First, we present the technical analysis of the system. We show how the rate of hydrogen production, here using the term utilization, is affected by the design of the renewable energy system (i.e. wind power capacity, battery size and technology) (ii) Second, we present the economic analysis. In particular, we provide assessments regarding the payback period of the installation. The results of the study let us conclude that (a) to maximize utilization, it is necessary to combine both source and storage components in a hybrid topology, and that (b) in the best scenario, PV co-exists with wind power achieving 65.5% utilization and delivering a payback period in less than 6 years, when hydrogen is sold at at least 6 €/kg.**

Keywords: Power-to-gas (P2G), Renewable energy, PV park, Wind power, Lithium-ion, Battery storage, Electrolysis

I. Introduction

Hydrogen can serve as an energy carrier for long term storage [1–3] and can be used in many different applications, including: (i) backup power generation (with fuel cells or internal combustion engines (ICEs)), (ii) transportation, (iii) chemical industrial processes, (iv) gas boilers, (v) combustion turbines [4–7].

Hydrogen can be produced using different methods, each with its specific environmental impact [8]. Especially when produced through electrolysis powered by wind turbines or PV panels, the polluting emissions are considerably lower compared to conventional production methods based on fossil fuels [9]. Regarding the production cost, renewable energy electrolysis has been so far too expensive to compete and finally substitute SMR (Steam Methane Reforming) which is currently the standard method. Nevertheless, as prices of photovoltaics and wind turbines decline, we expect more such systems to become economically viable, also benefited from policies that promote green energy initiatives.

In general, studies concerning hydrogen production through electrolysis can be divided into two categories: (i) Grid to Hydrogen [10–14] and (ii) PV/Wind to Hydrogen [15–19]. In the first category the electrolysis is driven by the electric grid whereas in the second category the energy comes exclusively from a renewable energy source (PV and/or wind power). Needless to say, from an environmental point of view, all PV/Wind to Hydrogen projects are superior to Grid to Hydrogen.

This paper belongs to the second category (PV/Wind to Hydrogen). In the present paper, we summarize the most important results and conclusions derived from a techno-economic real case study. The project was conducted primarily by Ghent University, in cooperation with several industrial partners and governmental institutions (see Acknowledgements). The main project objective was to investigate to what extent hydrogen production can add value to an existing large-sized PV park. In comparison to previous studies, this paper contributes the following:

- We focus on the utilization factor of the electrolyzer knowing that this is the key performance index of the system.
- We investigate hybrid topologies, considering next to PV, also the contribution of wind power and battery storage.
- We carry out economic evaluations based on real CAPEX & OPEX data received from the participant partners of the project.
- We perform a year-long simulation of the system using real measurements (i.e., power and weather data) registered locally inside the PV park, at high time resolution (10 minutes timeslots).

Figure 1 gives an overview of the system topology. The electrolyzer consumes renewable energy derived either directly from the sources (i.e. PV park, wind turbines) or indirectly from the battery that has been charged by these sources. After the production phase, hydrogen is injected into a gas pipeline passing nearby the PV park; there the H_2

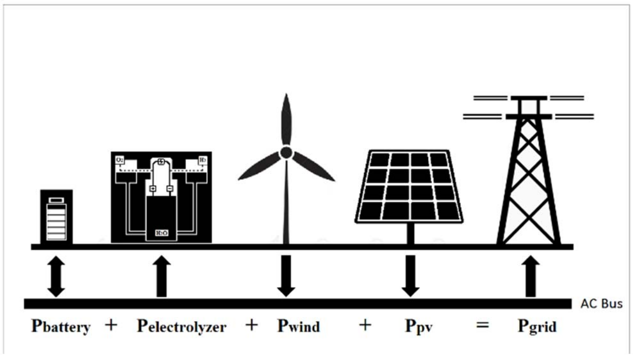

Figure 1: System Topology

is purchased by the company/owner of the pipeline. Under no conditions is the electric grid allowed to deliver power to the electrolyzer. The grid is simply used as a sink (note the direction of the arrow in Figure 1) absorbing the power surplus that exceeds the power capacity of the electrolyzer. We study three different scenarios:

A. Electrolyzer, 15 MW PV
B. Electrolyzer, 15 MW PV, 2 MW Wind
C. Electrolyzer, 15 MW PV, 2 MW Wind, Battery

In all scenarios, the power capacity of the PV park is fixed at 15 MW. Here, it is worth mentioning that by the time the feasibility study was finished, only the PV park existed. Therefore, in scenario B and C the presence of wind power and battery storage is hypothetical.

The rest of the paper is structured as follows. Section II is dedicated to the methodology, presenting for each component (electrolyzer, PV, wind and battery) all relevant data inputs and technical specifications. Section III presents the simulation results, comprising two parts: (A) techno-energetic assessments and (B) economic evaluations. Part III.A shows how the utilization of the electrolyzer is affected depending on the hybrid topology, whereas III.B quantifies the economic profitability of the system in terms of payback period. Finally, Section IV gives an overview of the main conclusions.

II. Methodology

A. PV park

The PV park is located in Zelzate, East Flanders, Belgium. The total surface covered by photovoltaic panels is estimated at 240,000 m^2. The peak power of the PV park is 15 MW. Since its commissioning, the active power generation is measured and monitored per timeslot of 5 min. The PV power profile was simulated using the measurements of the period 1 January 2016 – 31 December 2016.

B. Wind turbines

The simulation of the wind power profile was more complex, due to the absence of power measurements specifically for the location and type of wind turbines that were meant to be installed. The methodology followed in this study consists of three steps (for analytic information see [22]):

TABLE 1: WIND TURBINE TECHNICAL SPECIFICATIONS

Characteristics	**Specifications**
Type	XANT-L33
Number of blades	3
Rotor diameter	33 m
Hub height	55 m
Rated electrical power[1]	330 kW
Cut-in wind speed	3 m/s
Cut-out wind speed	20 m/s
Orientation	Downwind
Yaw control	Auto-yaw

1. Wind speed data at 10 m height was collected from a weather station for the concerned location and period of simulation.
2. Afterwards, the wind speed data was processed and converted into electric power data using the datasheets of the chosen wind turbine manufacturer (Table 1).
3. Finally, the power data of the single wind turbine was linearly scaled up to match the aggregate capacity of the assumed 6 wind turbines, each rated at 330 kW.

C. Electrolyzer

The technical specifications of the electrolyzer used in this study are presented in Table 2. The technology chosen is Polymer Electrolyte Membrane (PEM) electrolysis, which is more suitable for intermittent power supplies (e.g., PV, wind power) compared to alkaline electrolysis.

On the one hand, generally, the lower the size of the electrolyzer, in terms of rated power, the higher its utilization and thus the faster the payback period (years) of the investment. On the other hand, in order to increase the accumulated profit (€) by the end of the payback period, the electrolyzer needs to be big enough. Finally, the rated power was chosen to be 1 MW after considering budget limits as well.

As already mentioned, in order to evaluate the performance of the system, in all scenarios presented in the following section, the term utilization is used. We define 'utilization' as the ratio of the actual hydrogen quantity generated within a certain time period to the ideal hydrogen quantity generated assuming the electrolyzer continuously operates at its rated power. In this study, where the simulation period is one year the 'utilization' is calculated as follows:

$$\mathrm{U}_{\text{ELECTROLYZER}} = \frac{\text{Actual } \mathrm{H_2} \text{ quantity}}{\text{Ideal } \mathrm{H_2} \text{ quantity}} = \frac{\text{Actual } \mathrm{H_2} \text{ quantity}}{18\,\frac{\text{kg}}{\text{hours}} \times 8{,}760\,\frac{\text{hours}}{\text{year}}} \quad (1)$$

[1] at standard conditions (air density 1225 kg/m^3)

TABLE 2: ELECTROLYZER TECHNICAL SPECIFICATIONS

Characteristics	Specifications
Type	PEM
Rated stacked power	1 MW
Lifetime	70,000 – 80,000 h
Efficiency	60%
Load range	5 – 100%
Hydrogen production at rated power	200 Nm^3/h or 18 kg/h
Purity	99.99%
Output pressure	30 bar
Water consumption	0.019 m^3/kg H_2

TABLE 3: BATTERY TECHNICAL SPECIFICATIONS

Characteristics	Specifications
Type	Lithium NMC
Cycles	6,000
Efficiency	95%
DoD	100%
Self-discharge	Insignificant
C-Rate	1C

D. *Battery storage system*

Regardless of the size of the renewable energy sources, inescapably, there are time periods when the sun does not shine and wind does not blow sufficiently. During those periods of poor RES yield, the electrolyzer can operate using a back-up power supply. In our study, back-up is delivered by a battery storage system. The battery was simulated with the parameters shown in Table 3. Here, the chosen technology is Lithium NMC which exhibits several advantages such as high C-rate, efficiency and lifetime when compared to other technologies [3].

E. *Energy Management System (EMS)*

Both the PV source and the wind turbines operate at MPPT (maximum power point tracking). The EMS prioritizes the operation of the electrolyzer. As long as the total RES power (generated by the PV source and wind turbines) ranges within 0–1MW, it goes directly to the electrolyzer. The battery is charged (discharged) when there is a surplus (deficit) of power higher (lower) than the rated power of the electrolyzer, provided that its State-of-Charge (SoC) lies within the specified limits[2]. As surplus (deficit) we define the difference between the total RES power and the threshold 1 MW (rated electrolyzer power). The electric grid is never used to power either the battery or the electrolyzer, it is only used as a sink to absorb any surpluses happening when the RES power exceeds the sum of the battery's and electrolyzer's power.

III. RESULTS

A. *Techno-energetic assessments*

The results presented in Table 4 are the utilization of the electrolyzer and the total hydrogen quantity produced for the period 1 January 2016 – 31 December 2016. In the following, we compare how utilization is influenced by the system topology under consideration (scenario A, B and C). We also present Figures 2, 3 and 4 for each scenario A, B and C respectively, showing all relevant power profiles (i.e. electrolyzer, PV, wind, battery) for the two-day period 16 April 2016 – 18 April 2016.

TABLE 4: TECHNO-ENERGETIC RESULTS

	H_2 produced (kg)	Utilization (%)
Scenario A	65,495	41.5
Scenario B	103,000	65.5
Scenario C	103,950 – 135,550	66.1 – 86.2

1) Scenario A: Electrolyzer, 15 MW PV: The participant components are the PV park and the electrolyzer. This is the basic scenario where PV is the only source; neither wind power nor battery storage is included. Despite the fact that the PV park is relatively overdimensioned to the size of the electrolyzer, the utilization is merely 41.5%.

As shown in Figure 2 the electrolyzer operates at its maximum power during the day, whereas it is completely switched off after the sunset. It was concluded that at 41.5% utilization the investment potential in such system is quite limited and therefore we proceeded to the development of scenario B where PV co-exists with wind power.

2) Scenario B: Electrolyzer, 15 MW PV, 2 MW wind: The system consists of the PV park, 6 XANT L-33 wind turbines and the electrolyzer. The reason to consider exactly 6 medium-sized wind turbines and not more is due to space limitations.

The utilization of the electrolyzer is 65.5%. This is an increase by 24.0% compared to scenario A. Wind power plays clearly an important role in increasing the utilization even though the total aggregated power capacity of the wind turbines is much lower than that of PV. Obviously, wind power allows extension of the operation of the electrolyzer after sunset, therefore increasing the total annual hydrogen quantity produced from 65,495 kg to 103,000 kg.

For the given site, at 65.5% the utilization is maximized if only RES are deployed. To further increase the utilization, a battery storage system is required.

3) Scenario C: Electrolyzer, 15 MW PV, 2 MW wind, battery: Here, the participant components are the PV park, the electrolyzer, 6 XANT L-33 wind turbines and a Lithium NMC battery system. We simulated variation of battery capacity between 0.05–10 MWh. The utilization lies in the range of 66.1–86.2%.

As expected, bigger capacities result in higher utilizations and the extent to which scenario C outperforms scenario B depends on the size of the battery. Comparing Figure 4 to Figure 3, we notice how the battery (in this case 1 MWh) adds value to the system by increasing the operation time especially after the sunset and during night time. For the case shown in Figure 4, the battery capacity is not big enough to notice a significant difference in the power profile of the electrolyzer compared to Figure 3.

[2] Here, we consider a 100 % Depth of Discharge (DoD), therefore we cycle the battery over its entire energy capacity.

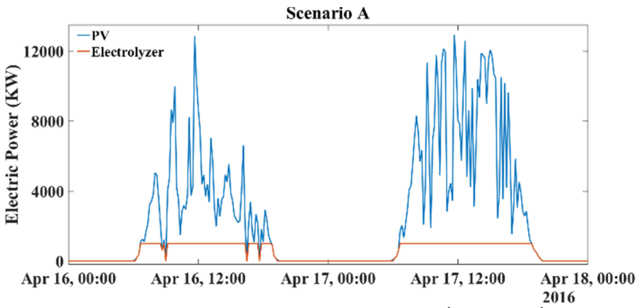

Figure 2: Scenario A: Power profiles during 16th April–18th April

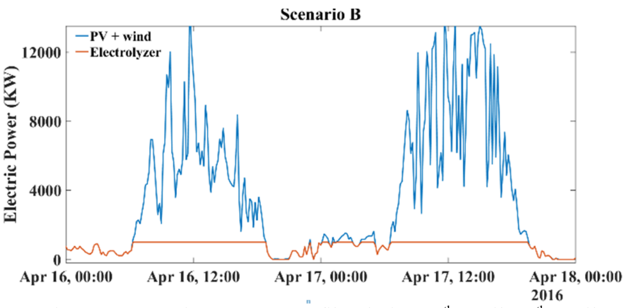

Figure 3: Scenario B: Power profiles during 16th April–18th April

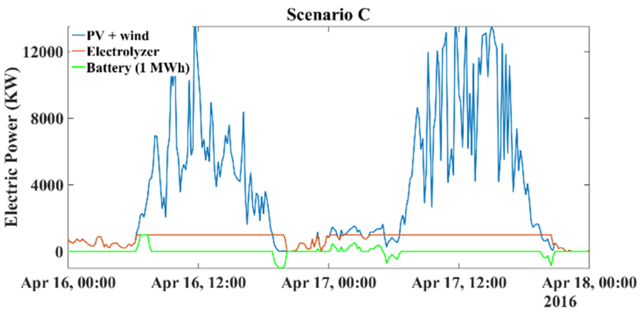

Figure 4: Scenario C: Power profiles during 16th April–18th April

B. Economic evaluations

The economic evaluations presented in this section concern scenario A and B. For Scenario C and further analytic information, we refer to [22].

We must emphasize that in our economic evaluations we assume that the renewable energy sources pre-exist, meaning that, apart from the CAPEX & OPEX of the electrolyzer, no expenditures are foreseen for installation of PV or wind power. In other words, we consider hydrogen production as an additional asset aiming to increase the value proposition of a renewable energy installation that was initially intended to be used as a conventional production unit injecting all its energy into the grid.

Table 5 gives an overview of all parameters and variables used to conduct the economic analysis. Regarding the electrolyzer, the investment comprises two parts: (i) capital expenditures and (ii) operating expenditures. The cost of each part is the average value calculated on three separate offers received from well-known manufacturers in the European region. [3] The electricity cost was estimated at 0.04 €/kWh, which is representative of the average price for the Belgian wholesale electricity market in 2017 [20]. Moreover, the study included the cost of water consumption [21] and a moderate rate of inflation. The price of hydrogen was varied between 4–7 €/kg, based on discussions between the industrial partners and the gas supplier.

The economic performance was evaluated by the payback period (in years) of the investment. The payback period is the time until the total revenue matches the sum of CAPEX & OPEX. It is worth noting that the industrial partners in our study claimed to be interested to invest provided that the payback period did not exceed 6 years. The results for scenario A and B are shown in Figure 5.

We observe that, for scenario B, hydrogen must be sold at least 5 €/kg to reach a payback period of less than 10 years. In case the price is higher than 6 €/kg, the payback period is less than 6 years. For scenario A, we see that the utilization is too low to reach a payback period in less than 6 years regardless of the fuel price.

Finally, it is important to mention that in the present case study the investment was benefited by its geographical location. The fact that a gas pipeline is present nearby the PV park simplifies the system design, in that it does not require installation of additional equipment (e.g., compressors, high pressure vessels) to store the fuel locally.

TABLE 5: ECONOMIC PARAMETERS & VARIABLES

		Value
Parameters	Electrolyzer CAPEX	1,750 €/kW
	Electrolyzer OPEX	4% [4]
	H_2O cost	4 €/m^3
	Electricity cost	0.04 €/kWh
	Inflation	2%
Variable	H_2 price (revenue)	4–7 €/kg
	Utilization	0–100%

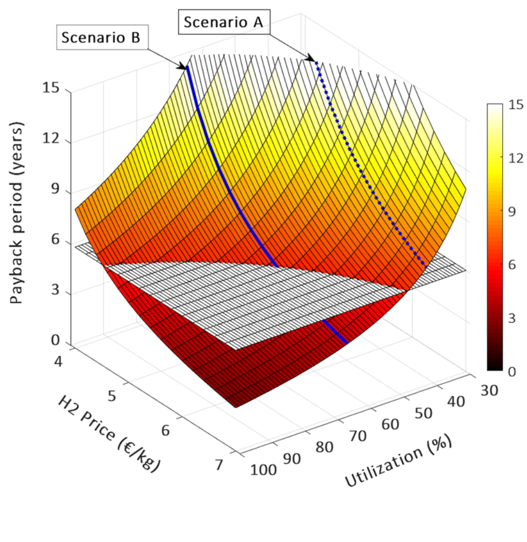

Figure 5: Payback period (Z axis) of the investment considering the parameters and variables of Table 5. The results for scenario A and B are illustrated with the blue lines, dashed and solid respectively.

[3] Not possible to disclose for confidentiality reasons

[4] 4% of the CAPEX per year

IV. CONCLUSIONS

The most interesting conclusions/notes from this feasibility study can be summarized as follows:

- Hydrogen production through electrolysis powered by PV and/or wind turbines can add value to a pre-existing installation provided that the utilization of the electrolyzer is sufficiently high. To maximize that utilization, hybrid topologies are needed, not only combining PV with wind, but also battery storage.
- A real-world case study exhibits various techno-economic constraints, often ignored in scientific papers. In this study for instance, due to technical limitations (e.g., limited free space, shadow effects on PV panels) it was not possible to install more than 6 medium-sized wind turbines.
- The economic results show that the payback period of the investment is less than 6 years if hydrogen can be sold for at least 6 €/kg. In the near future, the return of investment can be even faster considering the expected cost reductions to be made by manufacturers.

ACKNOWLEDGMENTS

This project was executed in cooperation with several partners from the industrial as well as the public sector. We especially would like to thank XANT (wind turbine manufacturer), KMI (royal meteorologic institute of Belgium), WaterstofNet, Total and Terranova Solar (PV park owner) for providing all information (e.g., datasheets, electric schematics, wind speed datasets, power measurements) necessary for the feasibility study.

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