Improving the utilization factor of a PEM electrolyzer powered by a 15 MW PV park by combining wind power and battery storage - Feasibility study

V. Papadopoulos[a,*], J. Desmet[a], J. Knockaert[a], C. Develder[b]

[a] *Ghent University, Faculty of Engineering and Architecture, EELAB/Lemcko, Belgium*
[b] *Ghent University - Imec, Department of Information Technology, IDLab, Belgium*

Abstract

So far, the biggest photovoltaic park in Belgium has been injecting all its energy into the electric distribution grid through a power purchase agreement with an electricity supplier. Due to decreasing and volatile wholesale electricity prices, the industrial partners/owners of the photovoltaic park are considering hydrogen storage in an attempt to increase the value proposition of their renewable energy installation. A major objective of the present work is to show how the utilization factor of the electrolyzer is affected by the design of the power supply system when the latter consists only of renewable energy sources instead of using the electric grid. Different hybrid designs were developed, by combining the existing photovoltaic source with wind power and state-of-the-art energy storage technologies (Vanadium Redox Flow or Lithium NMC). Finally, four scenarios were investigated, all considering a 1 MW PEM electrolyzer: A) 15MW PV, B) 15MW PV, 2MW Wind, C) 15 MW PV, 2 MW Wind, Battery, D) 15 MW PV, 15 MW Wind. The utilization factor was found as follows, for each scenario respectively: A) 41,5 % , B) 65,5 %, C) 66,0 - 86,0 %, D) 82,0 %. Furthermore, the analysis was extended to include economic evaluations (i.e. payback period, accumulated profit), specifically concerning scenario B and C. The results of this study lead to a number of conclusions such as: i) The utilization of the electrolyzer is limited when its power supply is intermittent. ii) Compared to PV, wind power makes larger contribution to the increase of the utilization factor, iii) 100% utilization can be achieved only if an energy storage system co-exists. iv) With a utilization factor at 65,5% scenario B can deliver a payback period in less than 8 years, if hydrogen is sold above 5€/kg. An analytic overview of all conclusions is presented in the last section of the paper.

Keywords: Power-to-Gas, renewable energy, PV park, wind turbines, battery storage, PEM electrolysis

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1. Introduction

Nowadays, the energy sector is undergoing an unprecedented transition with large investments in renewable energy sources taking place all over the world. In particular, over the last decade, projects regarding wind turbines and photovoltaics have made a considerable progress. Investments in photovoltaics and wind turbines will continue expanding, under the current status of a global renewable energy driven policy followed since the Paris Agreement [1]. However, the increasing penetration of both solar and wind power happens at the expense of some technical challenges. Since the energy yield provided by these sources is uncontrollable and not easy to predict, it will become gradually more difficult to maintain a balanced electric grid. Large amounts of renewable energy will have to be curtailed, unless energy storage systems are deployed [2, 3, 4].

In general, energy storage systems can be classified into three categories: i) short-term storage (sec-min), ii) medium-term storage (min-hours-days), iii) long-term storage (days-months) [5, 6]. Among these categories, especially, long-term storage systems can make a crucial contribution by absorbing renewable energy over extended periods of time without exceeding capacity limits. Long-term storage can be implemented by units with high energy densities and very low rates of self-discharge. Hydrogen is considered to be one of the most appropriate energy carriers for long-term storage [5, 7, 8]. In addition, hydrogen can provide several services in different sectors such as: i) backup power generators (fuel cells or internal combustion engines (ICEs)) ii) transportation sector iii) chemical industrial processes iv) gas boilers v) combustion turbines [9, 10, 11, 12].

Among those sectors mentioned above, hydrogen has been used until now mostly for chemical industrial processes. For the rest, it has not yet reached commercial success. An explanation for this lies in the fact that electromechanical power generators (i.e. fuel cells and ICEs) making use of hydrogen are still under development [13]. Other explanations can be attributed to the need for demonstration projects, limited political incentives and the current public acceptance [13]. Finally, a major factor impeding the commercialization of hydrogen applications is the absence of a well-established infrastructure; by this meaning production, transport and distribution of the fuel [14, 15]. In order to accelerate the

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[*] Corresponding author

Email addresses: `Vasileios.Papadopoulos@UGent.be` (V. Papadopoulos), `JanJ.Desmet@UGent.be` (J. Desmet), `Jos.Knockaert@UGent.be` (J. Knockaert), `Chris.Develder@UGent.be` (C. Develder)

progress of a hydrogen economy, all these challenges need to be resolved. The present work can be regarded as a contribution to the research domain addressing specifically the minimization of the hydrogen production cost.

Depending on the primary energy source (e.g. electrical, thermal, photonic etc.) different hydrogen production methods exist; each one having its own environmental footprint [16, 17]. A recent study has shown that hydrogen production through electrolysis driven by photovoltaics and/or wind power exhibits by far the lowest environmental impact, compared to conventional methods based on fossil fuels [18]. So far, hydrogen production through electrolysis has been too expensive to compete against fossil fuel production methods such as steam methane reforming (SMR) [19]. However, as the price of photovoltaics and wind turbines decreases in combination with more austere regulations towards environmentally friendly solutions, renewable energy electrolysis becomes more attractive.

In the next two paragraphs, a short review of previous studies is given addressing the feasibility of Power to Hydrogen projects from a techno-economic point of view. These studies can be divided into two categories: i) Grid to Hydrogen [20, 21, 22, 23, 24], ii) PV/Wind to Hydrogen [25, 26, 27, 28, 29]. The difference is that in the first category the electric grid is used as the main power supply to drive the electrolytic process, whereas in the second category the power supply is exclusively a renewable energy source (PV and/or Wind power) without any contribution from the electric grid.

Grid to Hydrogen studies: Kopp *et al.* [20] analyzed the performance of a 6 MW PEM electrolysis Grid to Hydrogen plant. Different market mechanisms were explored in order to generate revenue. It was concluded that through participation in the secondary reserve market the profitability of the plant can be improved. However, as stated by the authors, the study was carried out without considering the required capital expenditures of the electrolyzer. In Ref. [21], an economic study of a Grid to Hydrogen system is presented. Here, one of the objectives is to identify the optimal wholesale electricity price at which the levelized cost of the system is minimized. The study considered both PEM and alkaline electrolysis. Other factors included in the analysis are the size of the electrolyzer and its degradation. One of the conclusions was that the utilization factor of systems making use of PEM electrolysis must be higher compared to systems with alkaline electrolysis in order to minimize the levelized cost. Another Grid to Hydrogen project is presented by Felgenhauer and Hamacher in Ref. [22]. In this project, hydrogen is intended to be used for fuel cell logistic vehicles in an automobile factory. The study shows clearly that the production cost of hydrogen is influenced considerably by the cost of electricity and the utilization factor of the electrolyzer. In addition, the authors suggest that research scientists should focus on renewable energy in order to reduce the production cost of the fuel. In Ref. [23], an economic study was conducted regarding a hydrogen refueling station, located in Halle, Belgium. The station is powered partially by the electric grid. The other part of the power supply is provided by wind and PV power. As stated by the author, no information was provided to assess the contribution of renewables to the total power supply and therefore the study was done considering as electricity price the average grid price of Belgian medium-sized enterprises. A complete overview regarding the cost of each component (e.g. electrolyzer, compressors, storage, civil works etc.) is presented in the paper. The results show that the production cost of hydrogen can be reduced at 10,4 €/kg as long as the utilization of the system is maximized and provided that the electricity price is 0,04 €/kWh. Walker *et al.* [24] simulated the economic performance of a Grid to Hydrogen plant considering different sizes of the electrolyzer (2 MW, 5 MW and 30 MW). Given an input value/threshold (e.g. 40 US $/MWh) a comparison was made with the hourly wholesale electricity price. When the wholesale price is higher (lower) than the input threshold, the electrolyzer operates at minimum (maximum) power. It is mentioned that the profitability of the plant is strongly dependent on the utilization factor of the electrolyzer. Moreover, it was concluded that with big-sized systems the investment can achieve internal rates of return in the range of 15 - 21 %.

PV/Wind to Hydrogen studies: A Wind to Hydrogen project is presented in Ref. [25]. In this study, the objective is to generate hydrogen that will be used in refueling stations for fuel cell vehicles, in Sweden. The researchers used HOMER (software tool developed by NREL) to calculate the levelized cost of hydrogen production. Two types of wind turbines were considered: i) type V112, ii) type V82. The results delivered a levelized cost in the range of 5,18 - 7,25 US $/kg and 6,52 - 9,62 US $/kg respectively for the type V112 and V82. In Ref. [26], different scenarios of hybrid renewable energy systems were investigated to optimize the design of off-grid systems in Saudi Arabia. The simulation was done considering input data (PV, wind) at hourly resolution. Although this research work does not focus explicitly on the production of hydrogen, its proposed methodologies and results are interesting to take into account. An important conclusion is that in an optimized configuration where hydrogen production makes part of the system topology, wind power co-exists with PV power instead of using single sources (only PV or Wind). In Ref. [27], the objective is to design a hydrogen fuelling station using only renewable energy sources. Given a specified demand to supply on daily basis 25 fuel cell vehicles, the researchers used HOMER to define an optimal combination of PV with wind power and battery storage. The resolution of the input data (i.e. wind speed, solar irradiance) used in this study is hourly. The results delivered a configuration at which the levelized cost of hydrogen production was in the range of 7,5 - 7,8 US $/kg. Hou *et al.* in Ref. [28] carried out a techno-economic study of a Wind to Hydrogen system. The system was simulated using hourly resolutions of electricity price and wind speed data. One of the conclusions was that generating hydrogen from the wind farm in order to re-inject it afterwards back to the grid (re-electrification) using fuel cells is not profitable. Nevertheless, if instead of re-electrification hydrogen is sold to the industry at prices above 5 €/kg high returns of investment can be achieved. In Ref. [29], the research goal is to design optimally a renewable energy source system in order to maximize the amount of hydrogen produced by alkaline water electrolysis. It is mentioned that optimization is achieved by combining PV with wind power. Furthermore, it was concluded that wind power delivered a greater contribution to the total production of hydrogen compared to PV.

This paper focuses exclusively on renewable energy electrolysis. Therefore it belongs to the category of PV/Wind to Hydrogen studies. Obviously, the reason for choosing to concentrate on renewable energy is that hydrogen is produced without any polluting emissions. On the contrary, in Grid to Hydrogen projects, at least for the moment, the largest share of the electric energy comes from fossil fuels and therefore in such cases hydrogen cannot be regarded as an emission free fuel. In comparison with the aforementioned PV/Wind to Hydrogen studies, one of the major differences of the present research work is that, here, the emphasis is laid explicitly on the utilization factor of the electrolyzer. It was attempted to investigate how the utilization of the electrolytic process is affected each time by considering different combinations with respect to the type and size of the energy source. Furthermore, in the present work, all simulations were done using relatively high time resolution data (10 minutes time step), in contrast to most previous studies on PV/Wind to Hydrogen where the resolution is hourly. In general, given the intermittent character of PV and wind power profiles, the accuracy of the simulation result increases with the resolution scale of the dataset. Finally, another distinguishing characteristic of this paper is that the analysis pays much attention to the performance of the battery storage system considering different state-of-the-art technologies.

An overview of the system topology is given in Figure 1. The electrolyzer uses renewable energy derived either directly from the sources (i.e. photovoltaic park, wind turbines) or indirectly from the battery that has been charged by the sources. Following the production process, hydrogen is injected into a gas pipeline passing nearby the photovoltaic park, where it is purchased by the company/owner of the pipeline. If a surplus of electric power occurs, exceeding the power capacity of the electrolyzer (or the combined battery-electrolyzer capacity) the energy is injected back to the grid.

Since the operation of the electrolyzer depends on the availability of renewable energy, its utilization is subject to a number of parameters such as weather conditions, size of renewable sources (i.e. power, capacity factor), size of the electrolyzer, battery characteristics (e.g. energy capacity, C rate, efficiency). Furthermore, the extent to which the electrolyzer is utilized plays a decisive role in the return of investment of such project. Considering the aforementioned two statements together with the existing techno-economic constraints, it was concluded to split our analysis into four separate scenarios:

(A) Electrolyzer, 15 MW PV
(B) Electrolyzer, 15 MW PV, 2 MW Wind
(C) Electrolyzer, 15 MW PV, 2 MW Wind, Battery
(D) Electrolyzer, 15 MW PV, 15 MW Wind

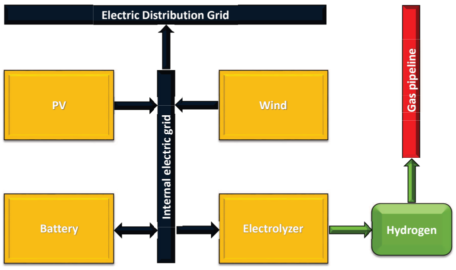

Figure 1: System Topology

Section 2 presents the methodology of the study. It explains the input data (i.e. wind speed, PV power profile) and the technical specifications of all participant components (PV, wind, electrolyzer and battery). At this point, it is worth mentioning that this methodology is not exclusively applicable to the present case study. It is a data driven approach that can be generalized to other locations as well, as long as the appropriate input data is available. Section 3 is dedicated to results, comprising two parts. Part 1 deals with generic techno-energetic assessments. The aim of Part 1 is to investigate how the utilization factor of the electrolyzer changes for each scenario (A, B, C and D) depending on the type and size of the source and storage component. Part 2 concerns economic evaluations (i.e. payback period, accumulated profit) only for scenarios B and C which seemed to be the most realistic to implement taking into account the constraints of the existing installation. Finally, all relevant conclusions, remarks and ideas for further research are given in Section 4.

2. Methodology

2.1. Photovoltaic park

The photovoltaic park is located in Zelzate, East Flanders, Belgium. To give an indication of its size, the total surface covered by photovoltaic panels is estimated at 240.000 m^2. With respect to the electric peak power, 15 MW is the highest ever measured value during sunny days. So far, the photovoltaic park has been injecting all its energy into the electric distribution grid [1]. Since its commissioning, the active power generation is measured and monitored per timeslots of 5 minutes [2]. In all scenarios presented in section 3, the photovoltaic power profile was simulated using the measurements of the period: 1 January 2016 - 31 December 2016.

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[1] The voltage level of the distribution grid at which the photovoltaic park is connected is 12.000 Volts

[2] This means 1 average active power registration every 5 minutes

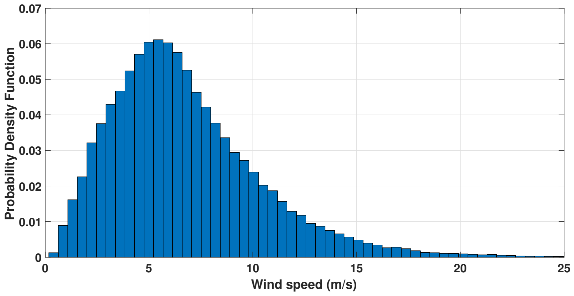

Figure 2: Wind speed distribution

2.2. *Wind turbines*

The simulation of the wind power profile was more complicated since no measurements were available for the location and type of wind turbines that were meant to be installed. The methodology followed in this study consists of three steps: Initially wind speed data was received and processed for the concerned location and period of simulation. Afterwards, the processed wind speed data was converted into electric power data using the datasheets of the chosen wind turbine manufacturer. Finally, the power data of the single wind turbine was multiplied by a constant to calculate the total wind power profile according to the desired wind power capacity. The methodology is further explained in the following paragraphs.

Wind speed data was received from a weather station located nearby the site. The wind speed measurements were carried out at 10 m height above the ground at 1 registration every 10 minutes, concerning the period: 1 January 2016 - 31 December 2016. However, the actual hub height of the wind turbines studied in this project was 55 m. In order to calculate the respective wind speed values at 55 m the following equation was used [30]:

$$\frac{v}{v_{10}} = (\frac{h}{h_{10}})^a \tag{1}$$

where,

- v is the wind speed (m/s) at height h
- v_{10} is the wind speed (m/s) at 10 m height
- a is the Hellmann exponent

In this study, the Hellman exponent was set at 0,5 , regarding the geographical topology of the site. This choice resulted in multiplying all speed values at 10 m by 2,35. The probability density function of the final calculated wind speed at 55 m is given in Figure 2. The average wind speed is 6,7 (m/s).

After having defined the wind speed profile, the active power profile of a single wind turbine can be calculated, based on the datasheets provided by the manufacturer. The technical specifications and the power-to-speed curve of the chosen type of wind turbine are given in Table 1 and Figure 3 respectively. The wind turbine can deliver up to 330 kW electric power. It has an automatic yaw control mechanism, meaning that it always follows the optimal wind speed direction. If the wind speed is very high (above 20 m/s) the wind turbine is shut down for protection. It is also important to note that, during periods of speeds below 3 m/s the wind turbine does not generate electricity. The probability of having wind speeds below that value is 12 % (See Figure 2).

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

Table 1: Wind turbine: Technical specifications

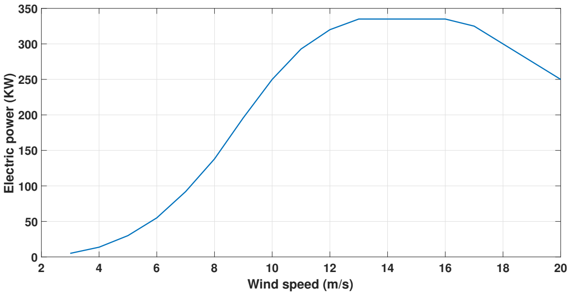

Figure 3: XANT L-33: Power-to-speed curve

Finally, the total wind power profile is formed by multiplying the wind profile of a single wind turbine with a constant depending on the desired power capacity. For example: A 2 MW wind farm is almost equivalent to six medium-sized wind turbines of the type XANT L-33: $330 \times 6 = 1,980$ MW.

2.3. *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 instead of alkaline electrolysis. In contrast to alkaline electrolyzers that require a minimum partial load, PEM electrolyzers can operate at full load range [16, 31, 20]. Therefore, PEM electrolyzers are more suitable for applications where the power supply is intermittent (e.g. PV panels, wind turbines).

The size of the electrolyzer, in terms of rated stack power, was chosen to be quite small compared to the size of the photovoltaic park in order to maximize its utilization.

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[3] at standard conditions (air density 1,225 kg/m^3)

Characteristics	Specifications
Type	PEM
Rated stack power	1 MW
Lifetime	70,000 - 80,000 h
Efficiency	60%
Load range	0 - 100%
Hydrogen production at rated power	200 Nm^3/h or 18 kg/h[4]
Purity	99,99%
Output pressure	30 bar
Water consumption	0,019 $m^3/kg\ H_2$

Table 2: Electrolyzer: Technical specifications

However, the option to install a very small unit was excluded, since the normalized cost (expressed in €/kW) of smaller installations becomes higher as the impact of fixed costs (i.e. manufacturing, project development, installation & maintenance) on the final price increases. Finally, the rated power of the electrolyzer was set at 1 MW.

Given the availability of a natural gas pipeline passing nearby the photovoltaic park and thanks to the high output pressure of the electrolyzer, it was preferable to inject all hydrogen directly into the pipeline. If however the pipeline did not exist, then all hydrogen would have to be stored locally. In such case, additional compressors and storage tanks must be installed, resulting in a more expensive investment. What is more, the efficiency of the system would be lower; regarding this study it would be lower than 60% primarily due to the presence of compressors.

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. The definition of the term is given as the ratio of the actual hydrogen quantity generated within a certain time period to the ideal hydrogen quantity generated if the electrolyzer was operating continuously at its rated power. In this study, where the simulation period was always one year the utilization was calculated as follows:

$$U_{\text{Electrolyzer}} = \frac{\text{Actual } H_2 \text{ quantity}}{\text{Ideal } H_2 \text{ quantity}} = \frac{\text{Actual } H_2 \text{ quantity}}{18 \frac{\text{kg}}{\text{hours}} \times 8.760 \frac{\text{hours}}{\text{year}}} \quad (2)$$

2.4. Battery storage system

Inevitably, there are always periods when the sun does not shine and the wind speeds are very low irrespective of the size of the renewable energy sources. The idea was to use a battery storage system to support the electrolyzer during those periods of poor renewable energy yields. The operation of the battery was simulated as follows: When the available electric power was higher than the rated power of the electrolyzer, the battery was charged with the surplus of energy. When the available electric power was lower than the rated power of the electrolyzer, the battery was discharged to supply energy to the electrolyzer as long as its capacity was not depleted.

Characteristics	Specifications	
Type	Vanadium Redox Flow	Lithium NMC
Cycles	>>12.000	6.000 [6]
Efficiency	75%	95%
Capacity fade	Insignificant	70% EoL
DoD	100%	100%
Self-discharge	Insignificant	Insignificant
C-Rate	0,2C	1C
Cost	400-600 €/kWh	400-600 €/kWh

Table 3: Battery: Technical specifications

With respect to the type of battery, it was difficult to identify a battery technology that best suited the intended application of this project. Based on literature reviews, It was decided to focus on two technologies: Redox Flow and Lithium-ion batteries. Although both technologies exhibit interesting characteristics especially for stationary grid-scale applications, there are many differences between them as explained in the following paragraph.

One of the most important advantages of redox flow compared to Lithium-ion is that the energy capacity component is independent from the power component, thus allowing a more flexible design. Redox flow batteries can endure many more cycles than Lithium-ion with almost zero capacity fade. New generations of Lithium-ion batteries can undergo high depths of discharge (DoD) comparable to those of redox flow batteries. However, this comes at the expense of accelerated capacity fade. The major advantages of Lithium-ion is that their efficiency is higher and that they are much cheaper per unit of power capacity (expressed in €/kW) [32, 8, 33].

Among all scenarios investigated in this study, only scenario C includes a battery storage system. The analysis in scenario C was done twice. The first simulation was done with a Vanadium Redox Flow battery whereas the second simulation was done with a Lithium NMC battery. Table 3 presents the technical specifications of both batteries. This information was derived from commercial datasheets. It is also worth mentioning that the presented batteries belong to the same price range[5] , therefore maintaining a fair comparison.

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[4] Considering the lower heating value of hydrogen: LHV = 119,9 (MJ/kg) [16]

[5] These price indications are based on offers received from different battery storage developers. Due to confidentiality agreements, the participant industrial partners preferred that the origin of these offers is not mentioned in the publication.

[6] Under a (dis)charging rate of 1C, at 100% DoD after 6.000 cycles the

3. Results

3.1. Techno-energetic assessments

All results presented in this section concern the period: 1 January 2016 - 31 December 2016. An overview is given in Table 4. The time scale of the simulation in each scenario was defined by the dataset with the lowest time resolution, which was the wind speed measurements at 1 registration every 10 minutes. Consequently, the power profile of the photovoltaic park, recorded at 1 registration every 5 minutes, was scaled-down to 1 average measurement every 10 minutes . At this point, it is important to note that PEM electrolyzers can respond very fast to command signals. The rate of hydrogen production can change from 0 to 100% within a few seconds [34]. Therefore, since the yield data changes much slower, it can be considered that the available for hydrogen production energy is always captured by the PEM electrolyzer at any time.

Scenario A: Electrolyzer, 15 MW PV

The participant components are the photovoltaic park and the electrolyzer. This the basic scenario where PV is the only source of electric energy; no contribution is made by wind power or by a battery storage system. The total annual energy yield delivered by the photovoltaic installation is 16.150 MWh. Comparing the power capacity of the PV park (15 MW) to the power capacity of the electrolyzer (1 MW), one could state that the photovoltaic installation is overdimensioned. Nevertheless, despite the abundance of solar energy, the amount of energy consumed by the electrolyzer was found to be merely 3.635 MWh or 22,5% of the total solar energy yield. The utilization of the electrolyzer is 41,5%.

The fact that no energy is generated during the night and the frequent presence of cloudy days are the most important factors affecting the utilization. Due to the low utilization factor, an investment in such system would not be very competitive. Consequently, the results of scenario A lead to the development of scenario B where PV co-exists with wind power.

Scenario B: Electrolyzer, 15 MW PV, 2 MW Wind

The system comprises the photovoltaic park, six XANT L-33 wind turbines and the electrolyzer. The owner of the photovoltaic park was planning, before the start of this study, to upgrade his renewable energy installation by adding wind power. Due to space limitations and geographical constraints, it was not possible to install more than six medium-sized wind turbines. This explains the choice in scenario B (and C) to consider precisely six medium-sized wind turbines and no more than that.

The additional amount of renewable energy produced by the wind turbines is 5.594 MWh. The energy consumed by the electrolyzer is 5.740 MWh or 26,5% of the total energy produced (PV and wind). The utilization of the electrolyzer is 65,5%. This is an increase by 24,0% compared to scenario A. It can be concluded that the contribution made by wind power is bigger, proportionally to its size, than the contribution of photovoltaic power. A way to explain this fact is that the capacity factor of wind power in this project is almost three times bigger than the capacity factor of the photovoltaic installation[7].

With the utilization factor at 65,5% scenario B proves to be more competitive than scenario A. However, this percentage is the maximum that can be achieved using only energy source components. To increase the utilization beyond this limit it is necessary to include also an energy storage component in order to allocate more efficiently the already available renewable energy yield. Such hybrid topology comprising PV, wind and battery storage has been studied in scenario C.

Scenario C: Electrolyzer, 15 MW PV, 2 MW Wind, Battery

The components participating in this scenario are the photovoltaic park, the electrolyzer, six XANT L-33 wind turbines and a battery storage system. As already mentioned, two cases were considered, one with Lithium-ion NMC and the other with Vanadium Redox Battery (VRB). For each case, the simulation was done repeatedly by changing the battery capacity within the range 0,05 - 10 MWh.

As expected, bigger battery capacities resulted in higher utilizations. The utilization for the Lithium-ion NMC case is 66,1 - 86,2%, which is slightly better compared to the 66,0 - 84,0% of the VRB case. Thanks to its higher efficiency and C rate, the Lithium NMC battery can transfer more energy to the electrolyzer than the VRB, given the same time period and battery capacity. Finally, it is noticeable in both cases that as the battery capacity increases the number of battery cycles per year declines. In other words, although bigger batteries make larger contributions to the increase of hydrogen production, their investment potential is lower compared to smaller batteries.

As expected, scenario C outperforms scenario B, where the percentage of improvement is obviously dependent on the size of the battery. However, in both scenarios B and C, it was assumed that the wind power capacity is maximized at 2 MW. What has not been mentioned yet and it is interesting to address is a system that consists of both infinite PV and infinite wind power (scenario D).

Scenario D: Electrolyzer, 15 MW PV, 15 MW Wind

The system consists of the photovoltaic park, forty five XANT L-33 wind turbines and the electrolyzer. One of the ideas proposed by the industrial partners, was to purchase electric

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battery capacity will have decreased at 70% of its initial value. At that moment the battery has reached its End-of-Life (EoL).

[7] The capacity factor is defined as the ratio of the actual energy yield produced within a certain period to the ideal energy yield if the unit operated continuously at its maximum power. In this project the capacity factors for PV and Wind are:

$$\mathrm{CP_{PV}} = \frac{16.150\ \mathrm{MWh}}{15\ \mathrm{MW} \times 8.760\,\frac{\mathrm{hours}}{\mathrm{year}}} = 12\%,\ \mathrm{CP_{Wind}} = \frac{5.740\ \mathrm{MWh}}{2\ \mathrm{MW} \times 8.760\,\frac{\mathrm{hours}}{\mathrm{year}}} = 33\% \tag{3}$$

energy from an external already existing wind farm, instead of installing new turbines inside the site. The wind farm was located at less than 300 m outside the photovoltaic park. It was therefore possible with a cable connection to transfer energy directly from the wind farm to the electrolyzer. The power capacity of the wind farm was estimated around 15 MW. Since no data was available, the power profile of the wind farm was simulated by multiplying the power profile of a single XANT L-33 by forty five: $330 \times 45 = 14,85 \approx 15$ MW

The energy yield produced by wind in this scenario is 41.960 MWh. The energy consumed by the electrolyzer is 7.183 MWh or 12,5% of the total energy produced (PV and wind). The utilization of the electrolyzer is 82,0%. This is an increase by 40,5% compared to scenario A. Proportionally to its size, scenario D performs worse than scenario B. The amount of additional hydrogen quantity produced by wind in scenario D is almost 1,7 times greater compared to scenario B. However, the total wind energy yield in scenario D is 7,5 higher than the wind energy yield in scenario B.

It was therefore concluded that by oversizing the renewable energy sources only, it is not possible to reach 100% utilization. Even with abundant solar and wind energy, the utilization is saturated due to the inevitable presence of unfavourable weather conditions (i.e. night-time, cloudy days, low wind speeds). In order to increase hydrogen production beyond the saturation point a battery storage system is needed.

3.2. *Economic evaluations*

The economic evaluations presented in this section concern specifically scenario B and C. Scenario A was left out of scope due its limited utilization (merely 41,5 %). Furthermore, scenario D was not considered despite its high utilization, since it required additional studies to clarify some technical and legal issues. It is important to note, that the entire economic study was based on the assumption that the renewable energy sources, both PV and wind, already exist. This means that hydrogen production comes only as a solution to increase the value proposition of the renewable energy installation that was initially designed to produce and provide electric energy to the grid. As a result, the capital investments needed to realize the photovoltaic and wind power installation were ignored.

The economic analysis was done considering the parameters and variables that are given in Table 5. The most important parameters are the costs of the electrolyzer and electricity consumption. Regarding the electrolyzer, the investment was split into two components: i) capital expenditures and ii) operating expenditures. The cost of each component was the average value calculated on three separate offers received from well-known manufacturers in the European region[8]. Furthermore, the electricity cost was set at 0,04 €/kWh, which is representative of the average price for the Belgian wholesale electricity market in 2017 [36]. Lastly, the study included also the cost of water consumption [37] and a moderate rate of inflation.

With respect to the price of hydrogen purchased by the gas supplier, there were no exact indications. Nevertheless, it was estimated that a realistic value would be within 4 - 7 €/kg. The battery capacity was also regarded as variable, as already presented in the techno-energetic assessments of scenario C. However, the analysis was done this time considering only the type Lithium NMC which proved to be more efficient compared to the VRB. Finally, the capital expenditure of the battery was selected to be the third variable. Although the available price indications suggested to set the variable within 400 - 600 €/kWh (See Table 3), it was decided to extend the range at 150 - 600 €/kWh, thus taking into account scenarios of significant cost reductions as expected in the near future [38].

The economic performance of each scenario was evaluated by two indicators: i) the payback period (years) of the investment and ii) the accumulated profit (€) realized 10 years after the system was commissioned. The payback period is simply the time in years needed to pass until the revenue equals the total capital and operating costs of the system. The accumulated profit is the difference between the revenue and the total capital and operating costs of the system precisely 10 years after the start of the project.

The results of scenario B are given in Table 6. Since no battery storage system exists in this scenario, the price of hydrogen is the only variable influencing the two indicators. In order to reach a payback period in less than 10 years, hydrogen must be sold at least 5 €/kg. If hydrogen is sold above 6 €/kg the return of investment is quite higher delivering a payback period less than 6 years.

The results of scenario C cannot be presented effectively using tables, since the outcome is always a function of three variables. The performance of scenario C can be illustrated in the form of a 4D space, where three dimensions correspond to the variable coordinates and the fourth dimension is colorized representing the result of the function (payback period or accumulated profit).

The payback period is given in Figure 4. The price of hydrogen remains the most important factor affecting the payback period. Another conclusion to note is that the payback period becomes higher as the battery capacity increases. This can be explained by the fact that the battery is getting more underutilized (lower number of cycles) as its size increases. It is worth mentioning that compared to scenario B, the payback period in scenario C is always higher (or slower).

The accumulated profit of scenario C, illustrated in Figure 5, is expressed as the additional accumulated profit (%) having as reference scenario B. All values in Figure 5 equal to 0% represent cases where the accumulated profit is equal or worse to that of scenario B. As it can be seen, there are cases where scenario C outperforms scenario B in terms of accumulation of profit. Such cases require that the maximum capital investment of the battery does not exceed 250 €/kWh. Furthermore, as it can be seen in some cases, for a given hydrogen price and

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[8] Once more, it is mentioned that it is not possible to disclose the origin of these offers. Readers who want to a draw a comparison with price indications presented in other papers can refer to [35, 28, 23]

		Scenario A	**Scenario B**	**Scenario C**		**Scenario D**
				Lithium NMC (0,05 - 10 MWh)	**VRB (0,05 - 10 MWh)**	
PV energy yield (MWh)		16.150	16.150	16.150	16.150	16.150
Wind energy yield (MWh)		N/A	5.594	5.594	5.594	41.960
Battery cycles		N/A	N/A	**424 - 179**	**242 - 159**	N/A
Electrolyzer	Energy consumed (MWh)	3.365	5.740	5.792 - 7.554	5.784 - 7.361	7.183
	H2 quantity produced (kg)	65.495	103.000	103.950 - 135.550	103.780 - 132.090	128.900
	Utilization (%)	**41,5**	**65,5**	**66,1 - 86,2**	**66,0 - 84,0**	**82,0**

Table 4: Techno-energetic results

		Value
Parameters	Electrolyzer CAPEX	1.750 €/kW
	Electrolyzer OPEX	4% of the CAPEX per year
	H_2O cost	4 €/m^3
	Electricity cost	0,04 €/KWh
	Inflation	2%
Variables	H2 price (revenue)	4 - 7 €/kg
	Battery capacity	500 - 5.000 kWh
	Battery CAPEX	150 - 600 €/kWh

Table 5: Economic evaluations: Parameters & Variables

Hydrogen price (€/kg)	**Payback period (Years)**	**Accumulated profit after 10 years (€)**
4	15	- 582.000
4,5	11	-13.800
5	8	554.000
5,5	7	1.120.000
6	6	1.690.000
6,5	5	2.260.000
7	5	2.830.000

Table 6: Economic evaluations: Scenario B

battery cost, the profit becomes higher as the battery capacity becomes bigger. In other words, given a certain period of comparison (in this experiment 10 years) there are cases where scenario C is more profitable than scenario B although the return of investment is always faster in scenario B.

4. Conclusions

An overview of the most interesting conclusions/notes drawn out of this feasibility study is presented below:

- Hydrogen production through electrolysis powered by photovoltaics and/or wind turbines can add value to an already existing renewable energy installation as long as the electrolyzer is not underutilized. Having PV as the only energy source (scenario A) leads always to low utilizations (below 50%) due to the inevitable presence of night-time, although the photovoltaic installation may be oversized compared to the electrolyzer. Compared to PV, wind power makes higher contributions to hydrogen production (scenario B) thanks to its higher capacity factor.

- A variety of geographical and technical constraints can impose limitations on the size of the renewable energy installation. In this project, apart from the 15 MW photovoltaic park it was possible to install up to six medium sized wind turbines (scenario B and C) with a total power capacity of 2 MW. As result, the utilization was directly saturated at 65%. To increase the utilization beyond that limit a battery storage system was also considered.

- The focus was laid on two battery technologies (scenario C) exhibiting competitive characteristics: i) Lithium-ion NMC and ii) Vanadium Redox Battery (VRB). The techno-energetic results show that Lithium-ion performs better than the VRB. Thanks to its higher C rate and efficiency, Lithium-ion can transfer more energy to the electrolyzer given a period of one year. The VRB could outperform Lithium-ion if the comparison was extended up to the moment that Lithium-ion reaches its end of life. By that time, the VRB would still have lots of cycles to provide. However, such scenario would require many years to pass (at least 15) exceeding the payback period of investment. Consequently, the Lithium-ion battery is preferable in this project.

- Even in a hybrid PV - Wind scenario where both sources are oversized and the available amount of renewable energy is abundant (scenario D), it is not possible to reach 100% utilization. There will always be periods when the sun does not shine and the wind speeds are very low. In this study, it was found that the probability of having

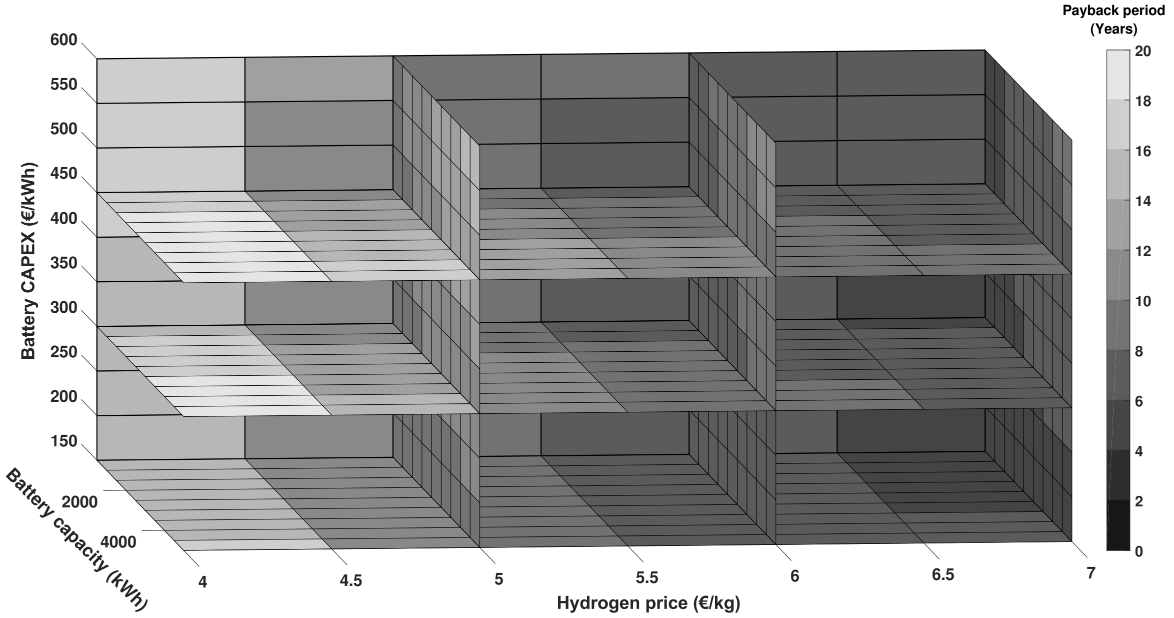

Figure 4: Economic evaluations: Payback period of scenario C with Lithium NMC

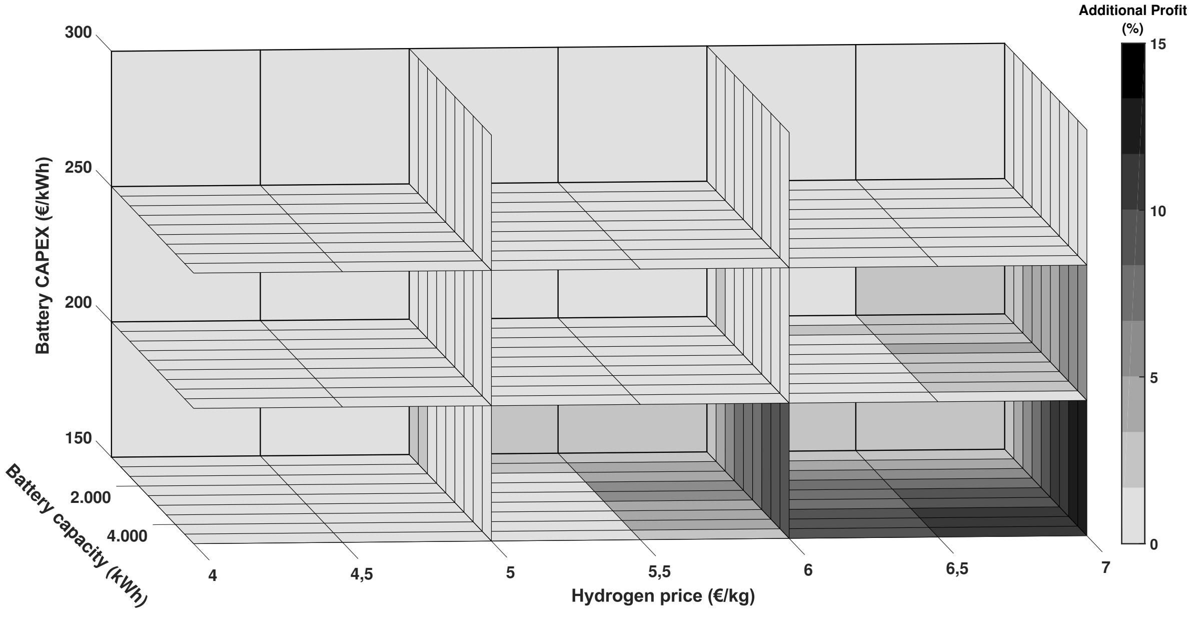

Figure 5: Economic evaluations: Additional accumulated profit of scenario C with Lithium NMC, having as reference of comparison scenario B

wind speeds below 3 m/s was 12% . At such low wind speeds, the wind turbine does not generate any power, therefore hydrogen production can be zero if at the same time photovoltaic power is absent. In order to maximize the utilization up to 100% a secondary storage system is needed to assist the electrolyzer during those periods of energy scarcity.

- The economic results show that scenario B can form a promising business case. The payback period of the investment can be below 8 years provided that hydrogen is sold at least 5€/kg. It is important to note once more that the entire study was done considering that all hydrogen generated at the output of the electrolyzer is directly injected into the gas pipeline. If this option did not exist, then hydrogen must be stored locally by using additional compressors and storage tanks. It was estimated that in such case the initial capital investment of scenario B could easily increase by 40 - 50 %.

- Under the current price indications received from battery developers (400 - 600 €/kWh), it is concluded that battery storage is for the time being too expensive to provide additional value regarding the application of this project. The payback period in scenario C is always higher (or slower) than in scenario B. Although, in terms of accumulated profit within a period of 10 years, there are cases where scenario C is better than scenario B, the battery capital investment must not exceed in all cases the price of 250 €/kWh.

Finally, it must be emphasized once more that the time resolution of all datasets used to carry out this techno-economic analysis was set at timeslots of 10 minutes. In comparison to many other studies where the time resolution is lower (e.g. 15 minutes, 30 minutes, 1 hour or even lower), a 10 minutes resolution leads to more accurate estimations. However, in reality, the characteristic frequency spectrum of both the photovoltaic and wind power profile lies in the range of seconds. Depending on the intensity of those second occurring variations, the validity of all studies conducted at lower resolutions is influenced. Consequently, the next goal of our research is to focus on high time resolution datasets (e.g. 1 minute, 30 seconds, 10 seconds) in order to evaluate the performance of the system under real-time conditions. Having datasets at such high resolution will enable us to estimate the simulation error when lower resolutions are considered.

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