PUNCH | Hydrocells

PAPER:

Techno-economic model and analysis of Production, Storage and Distribution (PSD) plants for the production of hydrogen from renewable sources

Authors: Andrea Almondo, Luca Borgia, Gianpaolo Martina, Romualdo Ruotolo, Enrico Testa

SUMMARY

Abstract

Projects of plants for the Production, Storage and Distribution (PSD) of green hydrogen are continuously increasing today, given the need to rapidly decarbonize human activities. The number of plants already in operations are moderately low in number, most of them were developed in the past only as demonstrators and few historical data are available. Hydrogen production cost is strongly affected by macroeconomics variations, e.g., the Russia-Ukraine geopolitics situation since beginning 2022, and by mid and long-term reduction in the cost of hydrogen technologies foreseen in the next years.

In this context, we developed a tool in Matlab/Simulink environment to perform techno-economic simulations in time domain of a PSD plant coupled to renewable energy sources models. The model complexity is consistent while keeping low computational effort. This tool allows to calculate the plant performance in terms of hydrogen production, energy flows and fixed/variable costs month by month. This tool was developed with physical and economic parametric values, allowing automatic scalability of the plant itself. In this way, it is possible to perform rapid and automatic sensitivity analyses, reporting and dimensioning for PSD plants. The tool, moreover, allows rapid plant layout adaptation to customize it to different Customers and scenarios. In this study, we used this tool to understand how fixed and operating costs, together with the plant utilization strategy, affect the final hydrogen cost. Different plant sizes and costs were considered. A strong non-linearity between techno-economic parameters and hydrogen cost is revealed. On average, the production of small quantities of hydrogen or by means of a total grid independency may not be the best solution in economic terms.

Paragraph 1 – Green Hydrogen Uses

The Intergovernmental Panel on Climate Change (IPCC) 2018 Special Report emphasized the need to rapidly decarbonize emissions-intensive sectors, including energy, agriculture, industrial processes, waste and transport to limit global warming to 1.5°C [1]. Some progress towards this target is ongoing, with Renewable Energy Sources (RES) technologies already delivering emission reduction today. In order to make unpredictable and discontinue renewable sources a reliable alternative to fossil fuels, it is necessary to couple them with an energy storage and distribution system capable to accumulate and distribute energy on demand. This in order to make them a reliable alternative to fossil fuels. Energy storage solutions are fundamental to optimize renewable energy availability, and they can provide even additional advantages, e.g., providing back-up power in the event of black-outs and allow renewable energy use to be optimized. They also make renewable energy transportable, enabling widespread use of zero-emissions electricity for vehicles and other applications not connected to the grid.

Batteries and hydrogen are two valid storage systems. Batteries are highly efficient and are best suited for use in passenger vehicles and to supply high volumes of power over short timescales. In contrast, hydrogen in gaseous form is energy dense and has great potential for use in large-scale, long-distance transport and longer timescales. To achieve a zero-emissions future, a combination of different energy storage technologies is mandatory. In addition to the potential usage as energy storage, hydrogen is already in use at large scale in many industrial and chemical processes, where the 96% of H_2 in the world is produced in grey form by methane reforming and other fossil fuels-based technologies[2].

A complete move to zero-carbon emissions would imply green hydrogen production by means of water electrolysis for both power storage and for industrial/chemical processes.

Paragraph 2 – PSD Systems Dimensioning, Constraints and Issues

A correct dimensioning and tradeoff analysis for an H_2 PSD plant must be correctly assessed, independently of how hydrogen is used. Different customer requirements must be considered at the same time: first of all, the minimum and maximum H_2 production; storage requirements and

---

[1] Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. *https://www.ipcc.ch/sr15/*. Accessed May 12, 2022.

[2] World Energy Council, 2019. New Hydrogen Economy: Hope or Hype? World Energy Council https://www.worldenergy.org/assets/downloads/WEInsights-Brief-New-Hydrogen-economy-Hype-or-Hope-ExecSum.pdf. Accessed May 12, 2022.

tolerance/penalties in case of H_2 shortages; grid availability and energy flows; on the other hand, the plant layout may be limited by constraints as for example the maximum space available for photovoltaic systems or other renewables installation; the space occupied by storage tanks together with operating pressures; safety distances and legal duties specific of each country. These requirements and constraints require a tradeoff between H_2 demand and production feasibility. The other key element that needs to be considered is the economic effort (capex, opex) of the plant and the need to reduce the Levelized Cost of Hydrogen (LCOH). The LCOH can be obtained in two steps dividing the total capital cost by the expected lifetime of the system (20 to 25 years), to determine an annual repayment. The annual repayment is then added to annual operating costs (including energy, water and maintenance). This total, divided by the amount of hydrogen produced per year gives the LCOH (in terms of euros per kilogram of H_2 produced).

In addition to these elements, other noise factors add complexity to the overall system dimensioning. Some of them are uncertainties in renewable energy availability; energy prices variation during the plant lifetime; few historical data available about actual performance, production and costs for this kind of plants; discontinuous hydrogen demand; advantageous prices of blue/grey hydrogen if compared to the green one.

All these factors, both of technical and economic nature, interact together, creating a complex system where many variables can play a key role in the overall PSD plant LCOH and therefore on its financial feasibility.

Paragraph 3 – PSD System Layout and Model Description

To face this complex system and to understand its sensitivity to techno-economic variations, a physical model of a PSD plant was developed in Matlab/Simulink environment and integrated with an economic model working in post-processing.

It is usually difficult to find a single system layout valid of the broad diversity of PSD plants in terms of application, size and complexity (from small power plants to multi-megawatt ones). The system proposed here can be considered as the minimum viable layout of green H_2 PSD systems, as it considers all the basic components required to allow a good cost estimation. Its layout is shown in Figure 1:

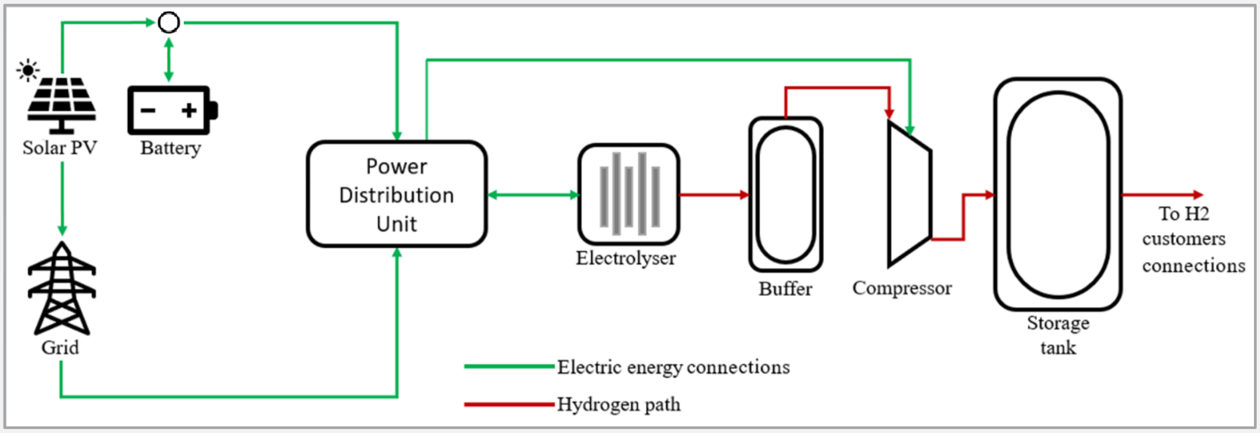


Figure 1 - PSD plant layout considered

Figure 1 shows a generic representation of energy and hydrogen flows in a PSD plant. The physical layout could have to be changed and adapted depending on country-specific regulations. This is especially true for what concerns the actual electric architecture and power conversion components not shown here above.

The economic model was developed considering the following variables:

- electricity cost from the grid, assumed as a variable price cost during 24 hours between three price values. This is representative of some Italian energy contracts,
- electricity selling price (due to renewables surplus), assumed as a single fixed price value during the day,
- capex and maintenance cost for each component, under the assumption of a linear correlation with the component size,
- plant lifetime and plant availability, and
- other fixed costs: engineering and commissioning costs.

The sum of all these costs, divided yearly and by the annual hydrogen production gives the LCOH in terms of [€/kg].

The simulation environment was set to run multiple sensitivity analyses by varying the following parameters:

- Electrolyzer (ELX) size (i.e., ELX rated power – kW),
- Photovoltaic (PV) size (i.e., PV peak power – kWp),
- Battery capacity – kWh,
- Capex costs for some components,
- Electricity selling and buying costs – €/kWh,
- ON/OFF strategy (detailed below).

Each simulation was run to follow an entire solar day for each month of the year (the average day was obtained from historical solar data), and the output was averaged for the entire year.

ON/OFF Strategy Implementation

An important outcome during the development of the techno-economic tool was the influence and importance that the plant control strategy has on the economic feasibility of the entire system. In this study, a simple, high-level ON/OFF rule was developed. Its purpose is to decide when and how each equipment can be set ON or OFF depending on solar radiation, daytime and other parameters or constraints that might affect the economic feasibility of the plant. Practically, the control strategy is an additional variable parameter when performing sensitivity analyses. In this study, after some trials, the two simple strategies shown below were proposed. They can be considered at two opposites:

- "ELX on solar" mode:
  - Electrolyzer: it goes ON in the morning when PV output is higher than the forecasted plant consumption. Then it is kept ON by PV and/or battery output during the day/evening, until the battery is depleted.
  - Battery: it is recharged only with renewables, when PV power is higher than the instantaneous plant power consumption; it is discharged to feed the plant as indicated above.
- "ELX H24 ON" mode:
  - Electrolyzer: it is always ON. In this case, there will be a buying from the grid when the battery is depleted.
  - Battery: as above.

In both cases, the ELX power is not modulated but kept at an optimal efficiency working point. Selling and buying to/from the electric grid is allowed in both cases, but the sell can occur only from solar panels excess, not from the battery (as shown in Figure 1).

Paragraph 4 – Case Studies and Results

Case Studies Considered

Three main case studies were considered. They are here defined according to the size of the PV array, whose peak power influences the sizing of ELX and battery, so that small, medium and big plants are defined and simulated. Table 1 shows the PV array peak power, ELX rated power and battery capacity ranges that were varied during the sensitivity analysis.

	Plant Size		
	Small	Medium	Big
PV power range [kWp]	50 - 250	500 - 2000	2000+
ELX power range [kW]	15 - 100	300 - 600	300 - 600
Battery capacity range [kWh]	50 - 500	500 - 3500	5000 - 12000

Table 1 – PV, ELX and battery size ranges for each case study considered

Results and Discussions

The results shown in the following paragraphs are obtained with current capex/maintenance costs and grid electric energy prices. The tool is anyhow capable to also analyze the sensitivity to strong energy cost variations as seen in the last months. Variation of these parameters are indicated where present.

Small Plant

From a first analysis, it is evident how the ON/OFF strategy impacts on the LCOH (Figure 2). As can be seen, in case of "ELX on solar" mode, there is a minimum cost occurring in correspondence of a specific battery size. This can be explained remembering that the ELX is producing H_2 only during daytime (from RES sources) and when the battery is able to feed it during the evening. So, there is a tradeoff between the higher H_2 production given by an extended ELX operating time and the increase in capex costs (linked to the increase in battery energy capacity). Instead, with ELX always operating, the results suggest to "avoid" a battery, with an LCOH always reducing when moving towards zero battery capacity. In this case, with current energy buying prices it is economically better to pay the required electric power to the grid instead of paying a large battery capex.

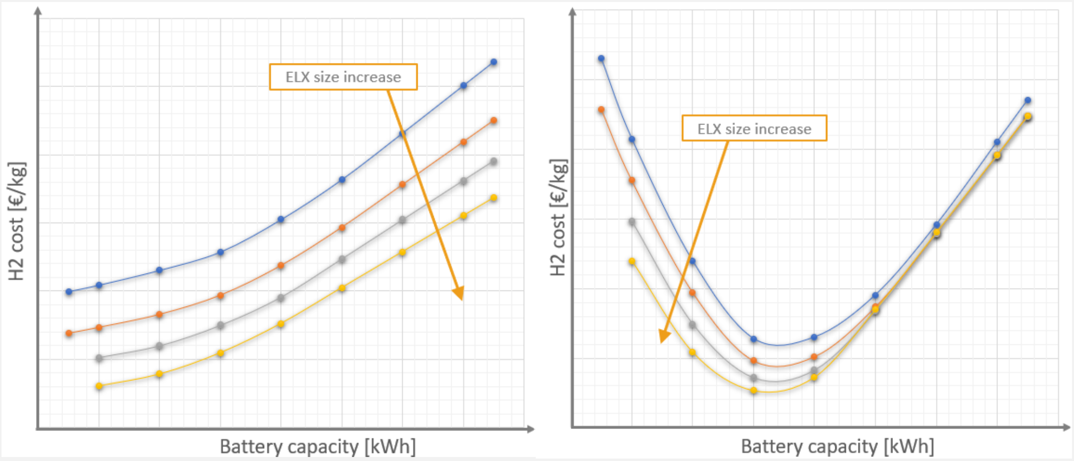


Figure 2 - Small plant – "ELX H24 ON" mode (left) Vs. "ELX on solar" mode (right)

In terms of cost comparison, the “ELX on solar” mode gives H2 costs that are 50% to 60% higher than the “ELX H24 ON” ones. This is easily explained by the lower ELX operating time during the day respect to an “ELX H24 ON” production. This suggests that a small plant using only PV plant energy will bring to less competitive hydrogen costs. Probably, it is better to increase the PV array and battery size to increase the RES storage during day. But again, there will be a tradeoff between capex and higher H_2 production and grid power selling.

Capex and electricity prices also have a strong impact on the final H_2 cost. A sensitivity analysis on the battery capex has shown that a potential reduction of 50% on energy capacity cost would bring the battery purchase favorable also for the “ELX H24 ON” strategy. As can be seen, Figure 3 now has the same trend of Figure 2 – right). The same result can be obtained by increasing the electricity cost (e.g., a raise of 15%).

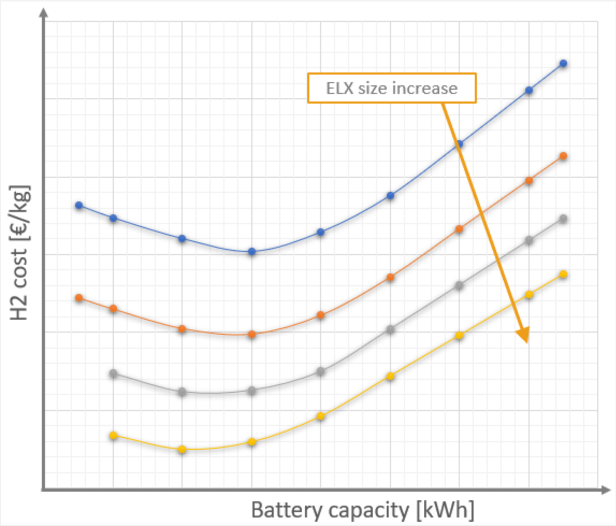


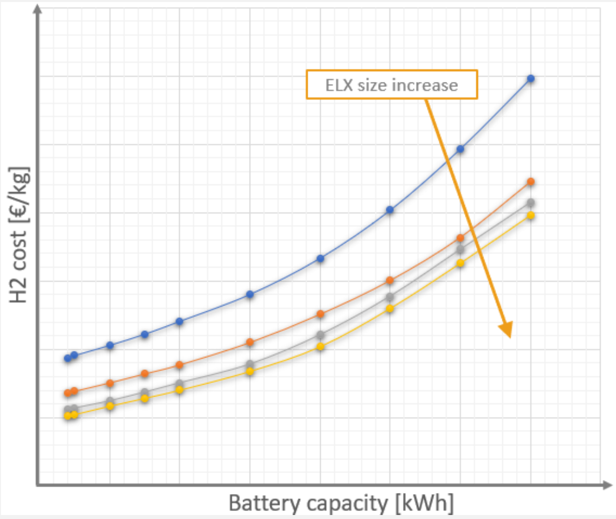
Figure 3 - Small plant – “ELX H24 ON” with halved battery capex

Considering the variation in the ELX size, it is clear how a bigger ELX – hence a higher H_2 production (but also capex), helps in reducing the LCOH for most of the situations. This means that the benefit in increasing H_2 production is higher than the disadvantage resulting from a higher capex.

As a note, the H_2 production in these simulations varied in the range of 3 to 8 tons per year (the minimum value occurring for “ELX on solar” mode).

Medium Plant

With PV sizes in the order of 1 MWp, in absence of limitations to H_2 production, the high quantities produced dilute the fixed costs (capex and opex) down to LCOH towards the range of 6-8 €/kg. The effect of the control strategy is less important for what concerns the LCOH behavior with the battery size. As can be seen in Figure 4, the two graphs show the same trend, suggesting to exclude the battery:



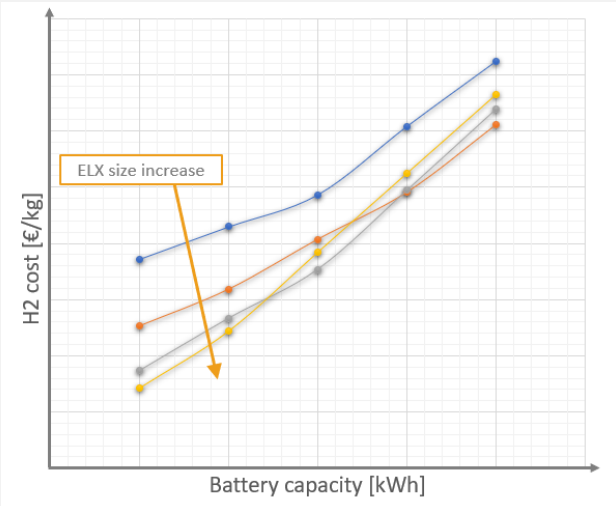
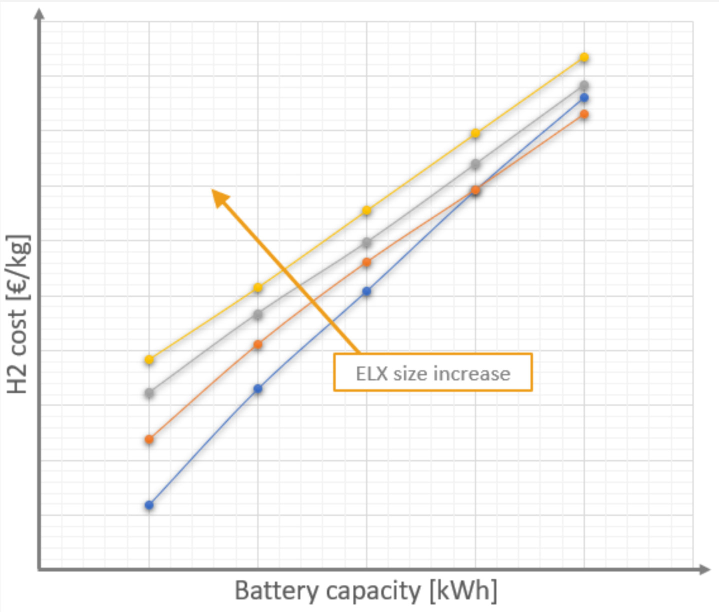


Figure 4 - Medium plant – “ELX H24 ON” (left) Vs. “ELX on solar” mode (right)

In terms of LCOH, the values for a mid-size plant are nearer between the two strategies respect to the small-size plant considered in the previous paragraph. The H_2 cost in case of “H24 ON” is still lower than in “on solar” mode (about 25% lower).



An interesting result can be found in the limit condition where the surplus of RES energy is used internally instead of selling it back to the grid (e.g., for other equipment apart from the PSD plant). This can be simulated imposing the selling price equal to the buying one (like a grid buy avoidance). As can be seen in Figure 5, in this condition, the smaller the ELX, the better.

In some way, this means that with high electricity selling prices (considering a current buy/sell ratio value in the range of 4-5), it is better to produce electric energy instead of producing hydrogen.

Figure 5 - Medium plant - Surplus of electric energy used internally (“ELX on solar” mode)

The next graph (Figure 6), correlates two representative capex values that may vary and influence PSD technology deployment in the next future with the diffusion of green technologies. This graph shows battery and solar capex variation for a fixed H_2 cost. All other parameters are blocked. Each line shows the maximum allowable capex for battery and PV array, for a given ELX size and H_2 production. Moreover, it shows how the increasing in the ELX size brings to an asymptote where a bigger ELX (and H_2 production) does not necessarily bring to a higher allowable cost.

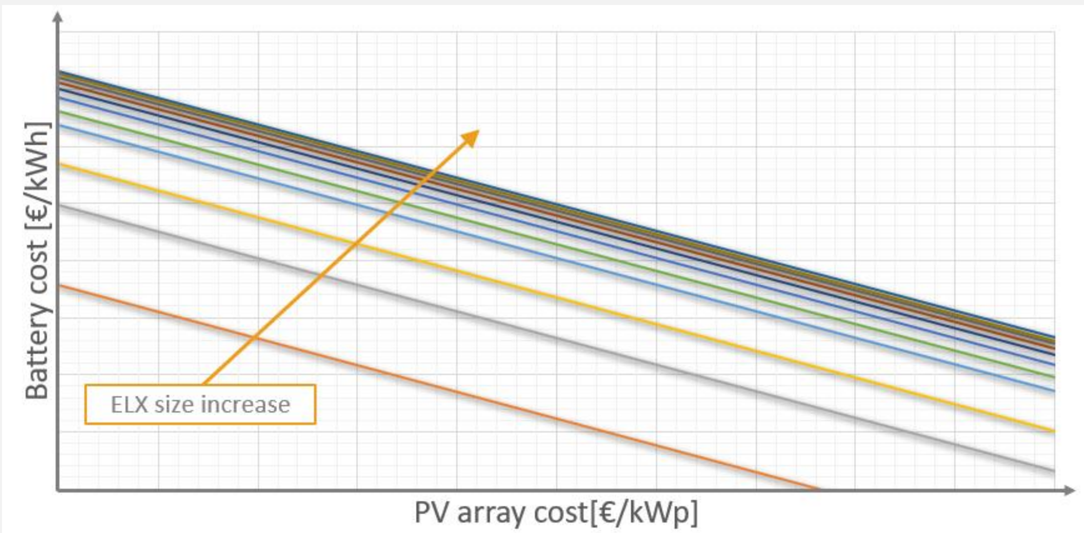


Figure 6 - Medium plant - allowable PV/battery costs at fixed H_2 cost

It is important to point out that the linear behavior and asymptote has a general validity: if the plot is drawn for other components capex on x and y axes, or for different plant sizes, H_2 costs or activation strategy, the curves show the same trendline.

Big Plant

As seen before, "H24 ON" strategy is usually better (in terms of cost) than "on solar" mode, for different plant sizes. In this paragraph, the big plant was tested with a mix between these two strategies in order to find different results.

For a fixed ELX size, the PV array and battery dimensions were scaled up to have a complete grid independency, while keeping H_2 production ongoing for 24-hours per day. This scaling was done for the worst month in terms of solar irradiance (i.e., to guarantee grid independency all the year). This dimensioning was called as "ELX on solar H24" mode. In other words, it is a "limit plant" capable to produce the maximum quantity of H_2 in green form only, for a fixed ELX size.

The results showed that for a 300 kW ELX and a plant located in center-Italy latitude, the battery capacity and PV peak power rises to 5.1 MWh and 2.2 MWp, respectively. This makes the plant land footprint important (with high efficiency modules at about 200 W/m^2, this implies to have a surface of about 1.5 soccer fields considering the active surface only). The correlation between ELX power, PV size and battery capacity to have grid independency resulted to be linear.

This “limit plant” size was then simulated together with smaller ones to compare a zero-grid buy condition with increasing buy percentages. Some results are given in Figure 7. At left, it is visible that, for current grid electricity costs, the minimum H_2 price occurs when there is a 25-40% of electric energy buy from the grid (note: grid buy percentage equal to zero corresponds to the “ELX on solar H24” plant).

In case of increase in electricity buying cost, this cost can prevail upon the battery/PV capex so that it is better to move towards a grid independency. This can be seen in Figure 7 – right, where it is assumed an increase in electricity cost of 50% with respect to the Figure 7 – left scenario. A further electricity cost increase would eliminate the local minimum.

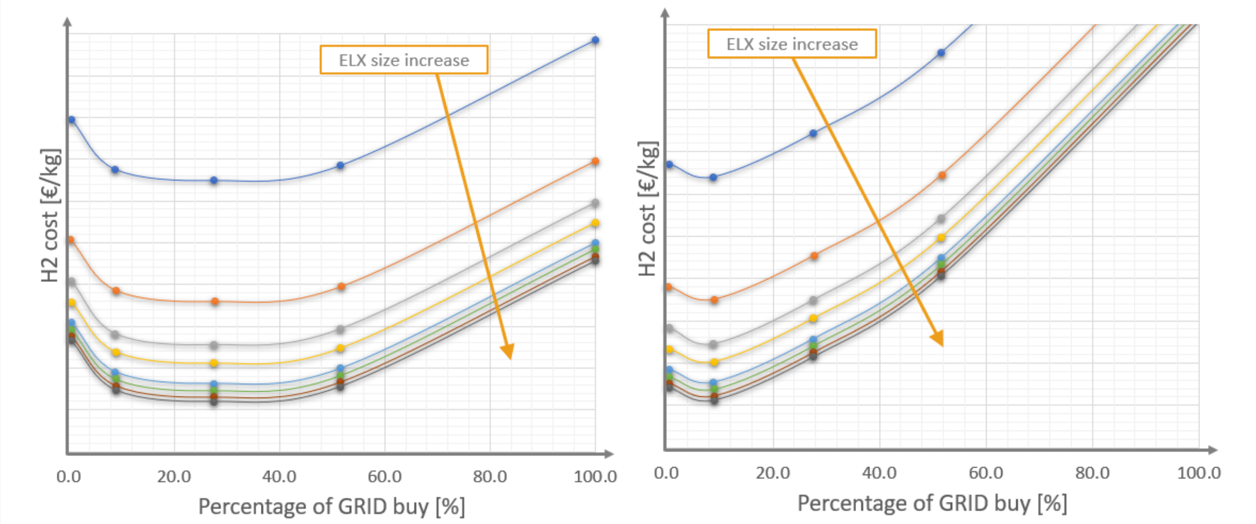


Figure 7 - Big plant - H_2 cost variation as a function of average annual electric grid dependance – average electricity cost (left) Vs. 50% increased cost (right)

To dimension an “on solar H24” plant (i.e., zero grid buy condition), the correlation between PV size, battery capacity and the ELX size is linear, as stated above. This linear correlation is still valid also in case of a partial buying of energy.

H_2 Cost Comparison Between Different Plant Sizes

To facilitate the understating the three sizes economic feasibility, Figure 8 compares the LCOH values obtained for each sensitivity point of the three plant sizes and for both the two ON/OFF strategies. Current capex, opex and grid costs were used. The x-axis contains the ratio between battery capacity and ELX rated power. This normalization allowed the comparison of different plant sizes on the same graphs. The y-axis does not start from zero value.

For the big plant, the plotted data are referred both to the zero-buy from grid and for different grid buy percentages. The big plant data is shown only in case of "ELX H24 ON" mode, since this plant was conceived as an always operating plant. For each of the five scatter plots, a linear trendline is shown to highlight the LCOH trend with varying battery/ELX size.

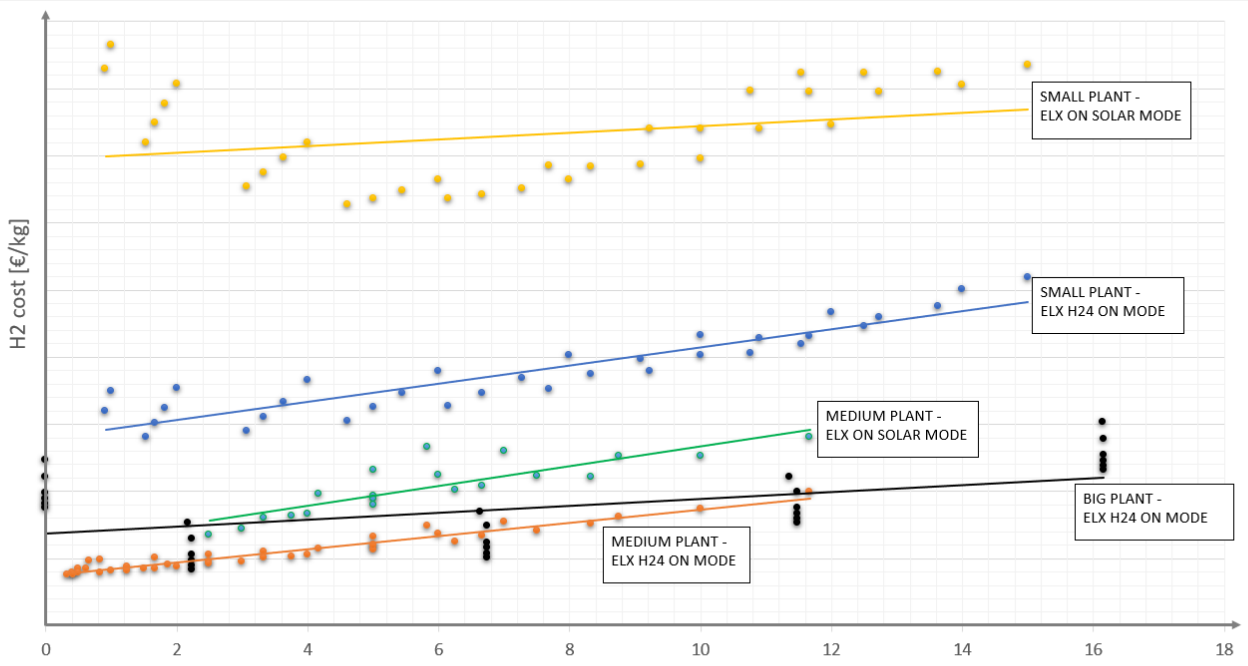


Figure 8 – LCOH between different plant sizes and ON/OFF strategy

These scatter plots were drawn with average capex and grid costs.

As can be seen, the higher cost occurs for the small plant, followed by medium plant and big plant. In all conditions where the same plant size is compared with two different ON/OFF strategies, the cost is always lower for "ELX H24 ON", as expected.

The gap between the small and medium plant (blue to orange line) amount to few Euros per kilogram for the "ELX H24 ON" graphs and about twice for the "ELX on solar" mode (yellow to green line). These plots show that a bigger plant (i.e., bigger H_2 production) always brings to lower LCOH values despite higher capex/opex costs, at least with present cost figures. Between a mid-sized and a big-sized plant, the LCOH is comparable, with the big plant becoming competitive when coupled to a big battery/ELX ratio. A bigger difference may be observed for big plants in the order of many multi-megawatt PV arrays (e.g., 10-30 MWp), but not simulated in this study.

Figure 9 provides the LCOH comparison in case of a reduction of battery capex by 50%. The gaps and relative position between each type of plant and strategy show the same trend of the previous case with standard battery cost in Figure 8. In this case, the linear trendlines highlight a lower LCOH with increasing the ratio of battery size vs ELX size, at least for small and big plants.

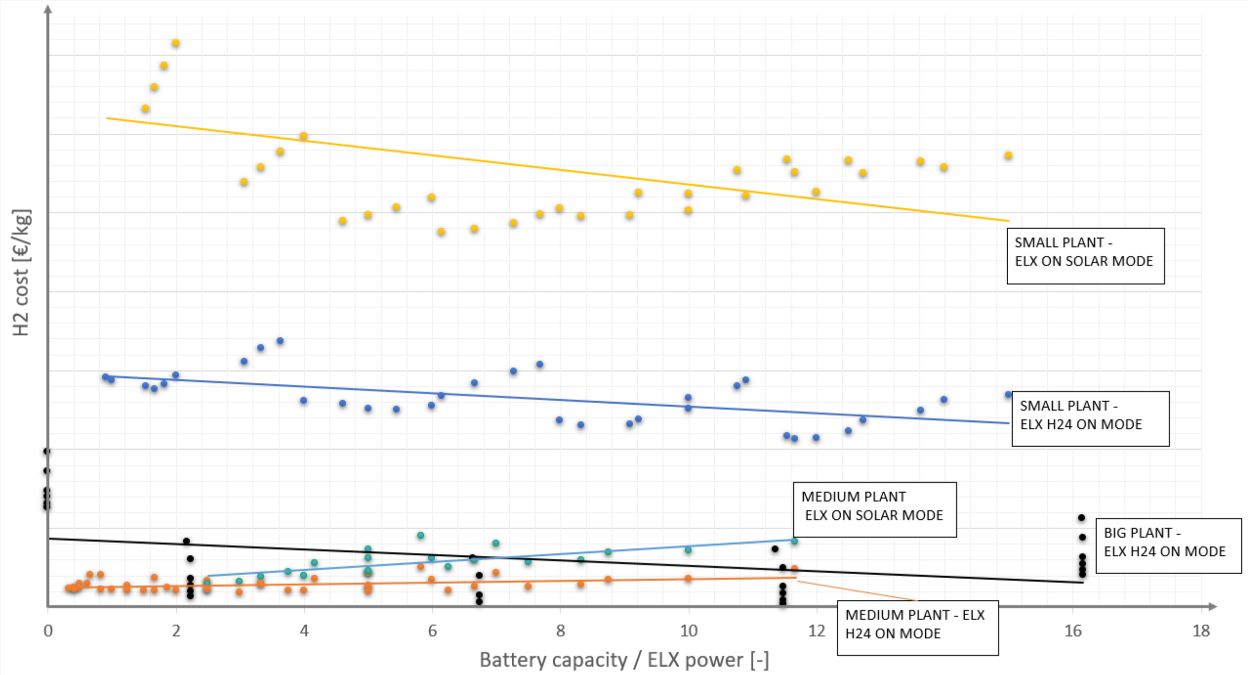


Figure 9 – LCOH between different plant sizes and ON/OFF strategy – battery capex reduced 50% respect to Figure 8

Paragraph 5 – Conclusions

The development of a simulation tool for green H_2 PSD plant to perform sensitivity analyses and preliminary dimensioning showed interesting results. As first outcome this study revealed that, even if hydrogen production with a total grid independency is feasible, this probably will not be the best choice in terms of LCOH. For sure, it allows the production of pure green H_2 but this probably will not be the best choice in terms of costs, as can be seen from the last figure. With current capex and opex costs, the LCOH is lowered substantially with a higher H_2 production. Small-sized plants are not economically favorable, given the higher impact of fixed and operating costs on the overall production.

This study also revealed a strong non-linearity and interaction between physical and economic parameters when trying to reduce the H_2 LCOH. This suggests that it is not possible to define general rules for the dimensioning of a PSD plant valid for all plant dimensions, H_2 production demand and economic conditions.

A possible roadblock in the lowering of H_2 production price consists in the fact that in real systems dimensioning there will be project boundaries and constraints not directly considered here (maximum cost allowed, min/max H_2 production and storage requirements, land footprint etc.). They will limit or force the plant dimensioning in certain directions. Plant performance degradation was not addressed here.

In addition to this complexity, attention must be paid to the fact that the techno-economic parameters (not only capex but also grid costs) may have future trends, fluctuations, and uncertainties – partially unpredictable, during the entire plant lifetime. This must be kept in mind for a proper economically feasible plant dimensioning.

A key role is played by the control strategy, and an optimal control may be a success element in reducing the impact of uncertainties and in providing optimal operating costs. A simple ON/OFF strategy was sufficient for the purposes of a preliminary plant dimensioning. It allowed an estimation of costs, hydrogen production and the best daily activation profile. However, advanced controls may bring the plant at optimal operations in terms of costs. Advanced controls may adapt the plant behavior to counterbalance short and mid-term fluctuations in commodity prices, renewables availability and H_2 demand. The control itself may be able to predict some fluctuations (e.g., based on machine learning). Such controls may also consider the durability of plant components in the overall plant control, to reduce maintenance costs during the plant lifetime.

To summarize, the layout and techno-economic analysis of a PSD plant need to be customized and developed – together with its basic control strategy – for every case study, paying attention to all constraints that will be present. Sensitivity analyses considering economic parameters are helpful to investigate the long-term economic feasibility and robustness of a PSD plant.

The tool developed for the techno-economic simulation of PSD plants, with its capability in adaptation to different scenarios, moves in the right direction for this purpose and to reduce uncertainties and degrees of freedom discussed above.

This paper is written by the Hydrogen Production, Storage and Distribution team from:

PUNCH | Hydrocells

PUNCH Hydrocells based in Turin in the "Cittadella Politecnica", is the answer by PUNCH Group to the energetic transition and the decarbonization challenge.

Our Hydrogen solutions covers the entire value-chain of hydrogen ecosystem: **Production**, **Storage and Distribution**, **Fuel Cells and Internal Combustion Engines**.

Address:
PUNCH Hydrocells Srl
Corso Castelfidardo 36
10129 Torino, Italy

LinkedIn
Website

For further information about this Paper, please contact:
Luca Borgia
Hydrogen Production, Storage and Distribution Program Manager and Chief Engineer at PUNCH Hydrocells
luca.borgia@punchhydrocells.com