On-site solar powered refueling stations for green hydrogen production and distribution: performances and costs

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Abstract. Today, the hydrogen is considered an essential element in speeding up the energy transition and generate important environmental benefits. Not all hydrogen is the same, though. The "green hydrogen", which is produced using renewable energy and electrolysis to split water, is really and completely sustainable for stationary and mobile applications. This paper is focused on the techno-economic analysis of an on-site hydrogen refueling station (HRS) in which the green hydrogen production is assured by a PV plant that supplies electricity to an alkaline electrolyzer. The hydrogen is stored in low pressure tanks (200 bar) and then is compressed at 900 bar for refueling FCHVs by using the innovative technology of the ionic compressor. From technical point of view, the components of the HRS have been sized for assuring a maximum capacity of 450 kg/day. In particular, the PV plant (installed in the south of Italy) has a size of 8MWp and supplies an alkaline electrolyzer of 2.1 MW. A Li-ion battery system (size 3.5 MWh) is used to store the electricity surplus and the grid-connection of the PV plant allows to export the electricity excess that cannot be stored in the battery system. The economic analysis has been performed by estimating the levelized cost of hydrogen (LCOH) that is an important economic indicator based on the evaluation of investment, operational & maintenance and replacement costs. Results highlighted that the proposed on-site configuration in which the green hydrogen production is assured, is characterized by a LCOH of 10.71 €/kg.

1 Introduction

The transition to a hydrogen-based mobility requires the development of an infrastructure that must be able to satisfy the hydrogen demand. Hydrogen refueling stations (HRSs) with on-site production from electric renewable energy sources (RES) are an interesting solution for assuring green hydrogen with zero CO_2 emissions [1-4] The advantages achievable by adopting this solution are: i) increasing the share of electricity produced by renewable sources, ii) helping the integration of the fluctuating and non-programmable renewables (solar and wind) in the electric grid, iii) providing grid balancing services, iv) producing "green hydrogen" able to assure a sustainable mobility. The main issue of these on-site RES powered HRSs is the green hydrogen cost that is currently too high and depends on both the plant size (hydrogen production capacity) and on the hydrogen source [4].
In recent scientific literature, several studies have been focused on techno-economic analysis of this type of plants, aiming to evaluate the levelized cost of hydrogen (LCOH). Gökçek and Kale [5] proposed a wind/solar/battery hybrid renewable energy powered refueling station on the island of Gökçeada, (Turkey). The hydrogen refueling station was sized for servicing 25 vehicles per day each having a 5 kg tank. The LCOH values were equal to $ 8.92/kg and $ 11.08/kg for the wind-PV-battery power system and the wind-battery system, respectively.
Zhao and Brouwer [6] evaluated the feasibility of a self-sustained hydrogen refueling station, in which a proton exchange membrane electrolysis unit fed by renewable sources (wind and photovoltaic plants) produced the specified hydrogen amount. Results showed that, for the photovoltaic (PV) system, the estimated LCOH was equal to $20.22/kg (by assuming an average levelized cost of electricity of $0.280/kWh). The LCOH dropped to 9.14 $/kg by reducing this cost to $0.103/kWh.
In [7] the authors studied an electrolysis/PV-Wind plant installed in Belgium. The estimated LCOH varied with the costs of electricity and the annual operation time, ranging from 10.3 €/kg to 18.0 €/kg.
In this study, a techno-economic assessment of an on-site hydrogen refueling station, based on hybrid PV-battery system integrated with an alkaline electrolysis unit and sized for a maximum hydrogen production of 450 kg/day, has been performed. In particular, in order to properly supply the electrolysis unit, a management strategy to optimize the electricity sharing between the PV field and the battery system has been defined. Moreover, in order to evaluate the contribution of each plant section (production section and compression & dispensing section) to the LCOH, a detailed costs analysis has been carried and the LCOHs of the plant sections have been calculated.

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2 Plant layout description and design

The proposed on-site HRS is based on a hybrid PV-battery system integrated with an electrolysis unit, to be installed in the South of Italy. Figure 1 shows the conceptual scheme of the proposed HRS. The electrolysis unit has a modular architecture consisting of 18 modules (the size of each module is 118 kW_p) operating a 16 bar and produces 450 kg/day (207 Nm^3/h) by converting 5040 liters/day of water in hydrogen and oxygen with an AC power consumption of 5.1 kWh/Nm^3. The produced hydrogen is pre-compressed up to 200 bar before entering the ionic compression unit IC90 (Linde technology), where it is compressed and stored up to 900 bar. During the refueling, the hydrogen is cooled at -40 °C according to the SAE J2601 protocol.

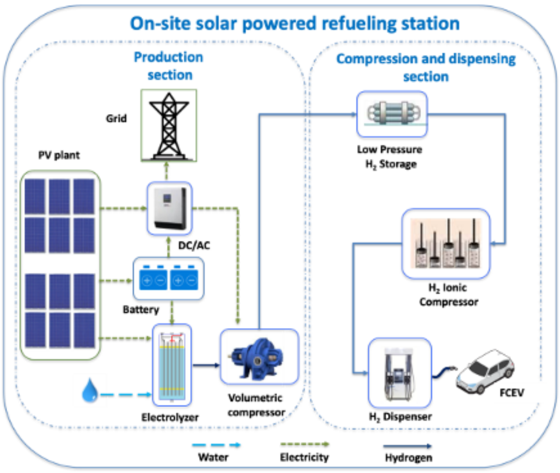

Figure 1: Scheme of the proposed on-site HRS station

The required electric power for the hydrogen production and compression is supplied by 8 MW peak PV plant and a 3.5 MWh Li-ion battery pack. In particular, each module of the PV plant consists of 250 W_p peak power mono-crystalline unit (Model 1Soletech 1STH-240-WH, Anodized Aluminum Alloy) with a fixed both azimuthal angle and tilt angle equal to 157.5° and 33°.

In Fig.2 the PV plant monthly electricity production is reported, while table 1 summarizes the size of the HRS components.

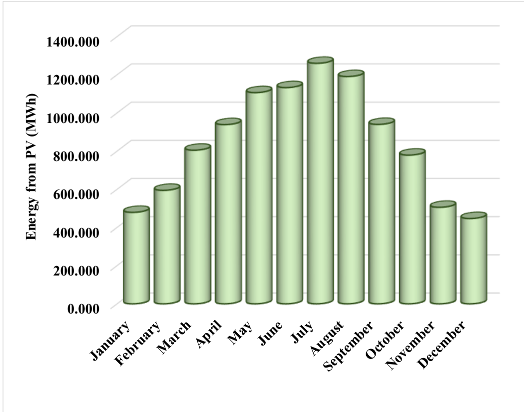

Figure 2: PV monthly electricity production.

Table 1. Size of HRS components.

Component	Size
PV (MWp)	8
Alkaline Electrolyzer (MW)	2.1
Pre-Compressor (kW)	23
Ionic Compressor IC90 (kW)	15
Li-ion battery (MWh)	3.5

3 Methodology

In order to properly supply the electrolysis unit for the hydrogen production, a management strategy for electricity sharing between PV plant and battery has been defined. The flowchart of the proposed management strategy is depicted in Fig.3. When the electric power generated by the PV plant is in the range 25-100% of the electrolyzer rated power, hydrogen is produced and stored; when the produced electric power is greater than the electrolyzer rated power (>100%), the electricity surplus is stored in the battery (considering that its initial charging state is 650 kWh) or delivered to the grid.

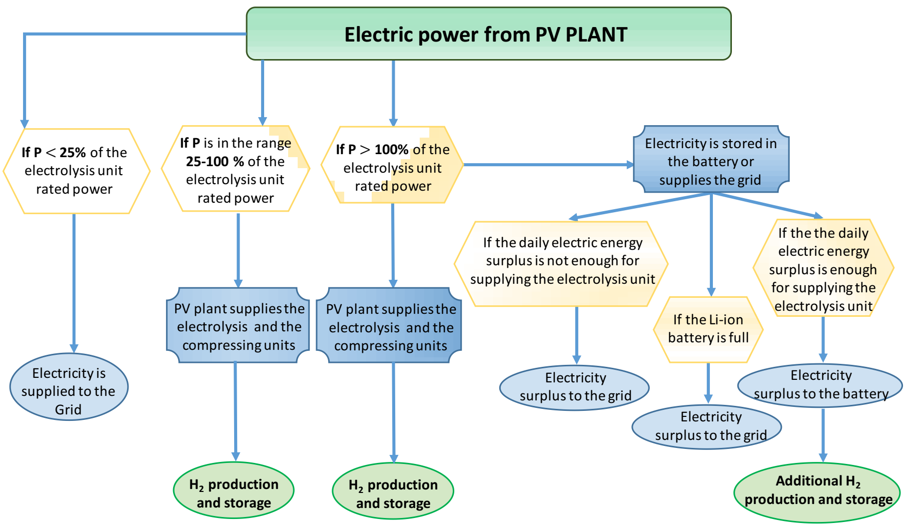

Figure 3: Management strategy flowchart

Moreover, when the electric power production is lower than the minimum load of the electrolysis unit (<25% of the rated power), the electric energy generated is diverted to the grid.
Figs.4 and 5 illustrate the results of the management strategy for the days of maximum and minimum hydrogen production, respectively.

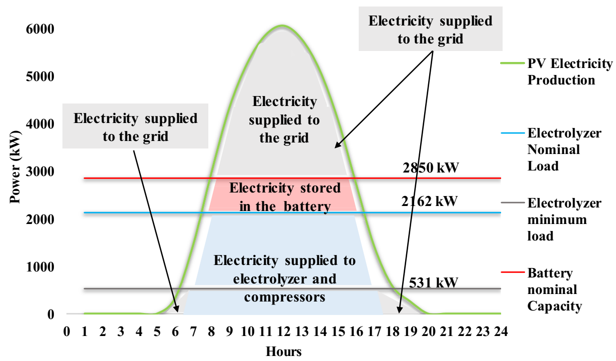

Figure 4: Day of maximum H_2 production

In Fig.4 it can be noticed that the PV field produces more electricity than that required by the plant (electrolyzer and compressors), allowing for the maximum hydrogen production of 400 kg. The electricity excess is partly stored in the Li-ion battery and partly delivered to the grid, according to the aforementioned management strategy. In particular, in this day, the battery allows to have an additional H_2 production of about 50 kg, allowing a maximum annual daily production of 450 kg, whereas the electricity surplus that has to be delivered to the grid is 20.4 MWh.

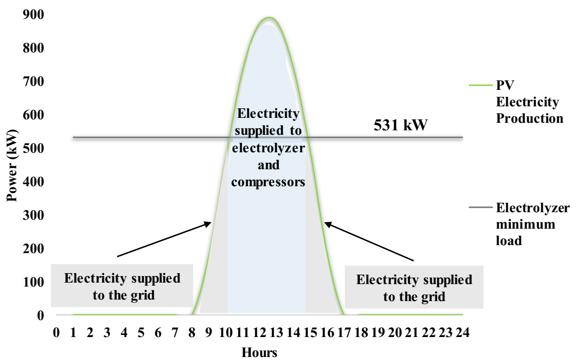

Figure 5: Day of minimum H_2 production

It is worth noticing that in the worst irradiation day (Fig, 5) the electricity generated by the PV field is always lower than that required by the electrolyzer at full load, and in some hour ranges (8h-10h; 15h-17h), the electricity generation is lower than that needed to supply the electrolyzer operating at minimum load. In this last condition, the electricity generated by the PV is diverted to the grid (1.3 MWh). On the other hand, when the electricity is greater than the minimum load of the electrolyzer (531 kW), the hydrogen production is assured, amounting for 56 kg in time range 10h-15h.

Fig.6 shows the annual hydrogen production, equal to 123.1 tons. Thanks to the battery pack it is possible to obtain an increase of the annual hydrogen production of about 11% corresponding to 14 tons.
The daily minimum and maximum hydrogen availability in the refueling station (or the capacity range of the station) are 56 kg and 450 kg, respectively.

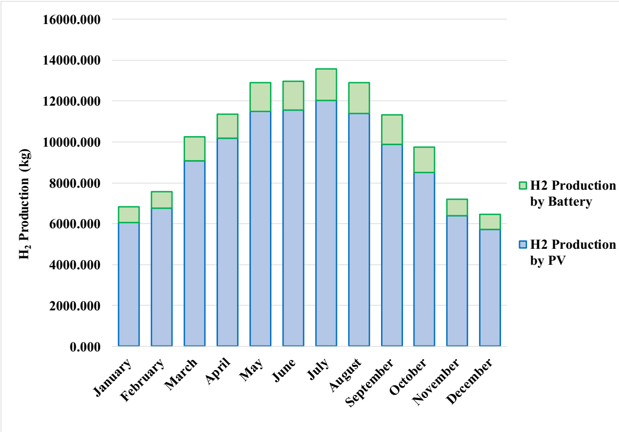

Figure 6: Monthly distribution of the annual hydrogen production

3 Economic Assessment

In order to define the HRS economic feasibility, the analysis has been performed by estimating the Capital Expenditure (CAPEX), the Operational Expenditure (OPEX), the Replacement Expenditure (REPLEX), and then by calculating the levelized cost of hydrogen LCOH that is the more important indicator among the economic evaluation indexes.

3.1 Plant cost definition

The costs of PV and electrolyzer have been assumed equal to 950 €/kW and 1100 €/kW respectively [8,9]. As concern the IC-90 Compressor, a capital investment cost of 648,000 € is assumed, according to ref [10]. For the Li-ion battery pack, a cost of 800 €/kW is assumed. According to the nominal HRS capacity, 2 Dispensing systems, with 4 nozzles are considered, each of which has a capital investment cost of 65,000 €.
The O&M cost of each component has been evaluated on yearly basis as a proper percentage of its initial investment cost. The percentages assumed for each plant component have been widely discussed by the authors in a previous paper [11]. For evaluating the cost due to the water consumption (computed as operating costs), the tariffs defined by the Italian Company ABC (sited in Naples) have been assumed [12] Based on these data, this cost consists of a fixed annual cost (€/year) and a cost variable according to water consumption (€/m^3). Considering that the annual water consumption is 1379 m^3/year, the fixed annual cost is equal to 18.12 €/year and the variable cost is equal € 1.006 for each consumed water cubic meter (m^3). Therefore, the total annual operating expenditure for water consumption results equal to 1,405 €/year.
As concern the electricity delivered to the grid, the

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assumed remuneration electricity price is equal to 50 €/MWh [13,14]. According to this value, the annual remuneration for the electricity sale amounts to 154,000 €/year.
Referring to the Replex, only one replacement (after 10 years) has been considered for the electrolyzer, compressors, Li-ion battery, dispensing and water system. Table 2 lists the CAPEX, OPEX and REPLEX for each plant's component.

Table 2. Total costs for HRS configuration.

Components	CAPEX (k€)	OPEX (k€)	REPLEX (k€)
PV modules	7600.0	120.1	-
Electrolyzer	2336.4	46.7	368.0
Compressor	239.6	19.2	239.6
Low pressure Storage System	450.0	9.0	-
IC90	648.0	25.9	-
Li-ion battery	2800.0	84.0	2800.0
Dispenser	260.0	7.8	260.0
Water System	7.83	0.3	7.83
Total (k€)	14,341.8	313.0	3,675.4

3.1 Levelized Cost of Hydrogen

The levelized cost of hydrogen ($LCOH$) methodology allows for accounting all the capital and operating costs of hydrogen supply chain. It is calculated as:

$$LCOH = \frac{Total\ Costs\ (€) - Electrical\ Revenue\ (€)}{H_2\ Annual\ Production\ (kg)} = \frac{C_{inv,a} + C_{rep,a} + C_{O\&M} - Rev_{el}}{M_{H_2}} \quad (1)$$

$C_{inv,a}$ represents the annual capital repayment, which is calculated by taking into account the total plant capital investment costs (C_{inv}), the plant lifetime (n), and the nominal interest rate (i):

$$C_{inv,a} = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \cdot C_{inv} \quad (2)$$

In particular, a plant lifetime equal to 20 years and a nominal interest rate equal to 3% have been assumed [15,16].

$C_{rep,a}$ is the annualized replacement cost and represents the annual cost rate to replace all components and parts that wear out during the plant lifetime. It is calculated as:

$$C_{rep,a} = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \cdot \frac{C_{rep}}{(1+i)^t} \quad (3)$$

where C_{rep} and t are the replacement cost and related year, respectively.
$C_{O\&M}$ represents the cost to guarantee the normal operation and maintenance of the plant; it is calculated on yearly basis.
Finally, Rev_{el} represents the annual revenue obtained by selling "electricity excess" to the grid. This term is considered in the eq. (1) as a negative cost.
In this analysis, in order to evaluate the cost incidence of each hydrogen supply chain section (fig.1), the $LCOH$ has been calculated as:

$$LCOH = LCOH_P + LCOH_{C\&D} \quad (4)$$

where $LCOH_P$ refers to the hydrogen production section and $LCOH_{C\&D}$ refers to the hydrogen compression and dispensing section.
Tables 3 and 4 list the cost items for the $LCOH_P$ and $LCOH_{C\&D}$ calculation, respectively.

Table 3: Individual cost item for $LCOH_P$ calculation

$C_{inv,a}$ (k€/year)	$C_{rep,a}$ (k€/year)	$C_{O\&M}$ (k€/year)	Rev_{el} (k€/year)	$LCOH_P$ (€/kg)
872.7	181.2	271.5	154.0	9.52

Table 4: Individual cost item for $LCOH_{C\&D}$ calculation

$C_{inv,a}$ (k€/year)	$C_{rep,a}$ (k€/year)	$C_{O\&M}$ (k€/year)	Rev_{el} (k€/year)	$LCOH_{C\&D}$ (€/kg)
91.3	13.0	42.7	-	1.19

The $LCOH$ for the considered HRS is 10.71 €/kg. This is a good value considering that the hydrogen production is totally renewable.
Fig.7 shows the $LCOH_P$ and $LCOH_{C\&D}$ incidence on the total $LCOH$. It is worth noticing that the production section affects the total $LCOH$ for about 89%, showing the greatest incidence compared to the compression and dispensing section.
The higher incidence on the $LCOH_P$ is due to $C_{inv,a}$, which affects it for about 66%.

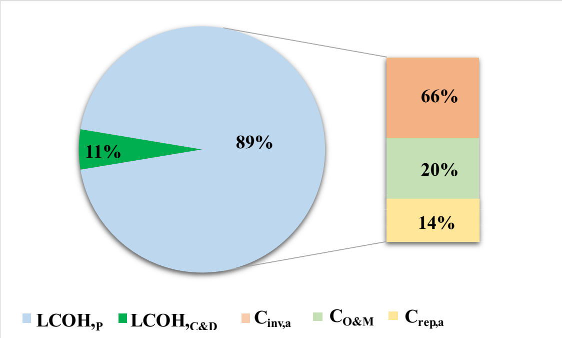

Figure 7: Incidence of items cost on the $LCOH$ of each section plant

4 Conclusion

This paper is focused on the techno-economic analysis of an on-site hydrogen refueling station (HRS) in which the green hydrogen production is assured by a PV plant that supplies electricity to an alkaline electrolyzer. A Li-ion battery pack is used to store the electricity surplus, while the grid-connection mode of the PV plant allows to export the electricity excess that cannot be stored in the battery system. The HRS consists of two main sections: the production section and the compression and dispending section. To properly supply the electrolysis unit a management strategy able to optimize the electricity sharing between the PV field and the battery system has been defined. According to this strategy the annual hydrogen production in the proposed HRS is equal to 123.1 tons. The daily minimum and maximum hydrogen availability in the refueling station (or the capacity range of the station) are 56 kg and 450 kg, respectively and thanks to the battery unit the annual hydrogen production increases of about 11% (14 tons).
The economic analysis has allowed to estimate the LCOH; in particular, the contributions of each plant section (production section and compression & dispensing section) on the LCOH value have been calculated, underlying the prevailing incidence of the production section.
Results highlighted that the proposed on-site configuration in which the production of green hydrogen is performed, is characterized by a LCOH of 10.71 €/kg.

2 References

[1] Alessandra Perna, Mariagiovanna Minutillo, Simona Di Micco, Viviana Cigolotti, Adele Pianese. E3S WEB OF CONFERENCES, 197, (2020)

[2] Dimitrios Apostolou, and George Xydis. Renewable and Sustainable Energy Reviews 113, 109292. (2019)

[3] Alessandra Perna, Mariagiovanna Minutillo, Simona Di Micco, Pasquale Di Trolio, Elio Jannelli. AIP Conference Proceedings 2191. 2201, p. 020127-020136, (2019)

[4] Alessandra Perna, Mariagiovanna Minutillo, Pasquale Di Trolio, Simona Di Micco, Elio Jannelli. Int J Hydrogen Energy, 46 (16),10059–10071 (2021)

[5] Gökçek, Murat, and Cihangir Kale. Energy Conversion and Management 161 (2018): 215-224

[6] Zhao L, Brouwer J. Int J Hydrogen Energy 2015;40:3822–37.

[7] Viktorsson L, Heinonen JT, Skulason JB, Unnthorsson R. Energies 10,1–15, (2017).

[8] Staffell I, Green R. Int J Hydrogen Energy 2013;38:1088e102.

[9] Schmidt O, Gambhir A, Staffell I, Hawkes A, Nelson J, Few S. Int J Hydrogen Energy2017;42:30470e92.

[10] Edmund G. Brown Jr., Governor, Calif. Energy Comm. (2019)

[11] Mariagiovanna Minutillo, Alessandra Perna, Antonio Forcina, Simona Di Micco, Elio Jannelli. Int J Hydrogen Energy 46(26):13667-13677 (2020).

[12] Napoli ABC. Adeguamento tariffario 2019.

[13] GESTORE MERCATI ENERGETICI (GME)-Mercato del Giorno Prima (MGP)