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Assessing the Levelized Cost of Hydrogen Production in a Renewable Hydrogen Community in South Italy

Alessandro Ciancio, Livio de Santoli
Department of Astronautical, Electrical
and Energy Engineering
Sapienza University of Rome
Rome, Italy
alessandro.ciancio@uniroma1.it

***Abstract*—The need to address climate change requires a shift towards more sustainable energy systems with lower greenhouse gas emissions. The emergence of Distributed Energy Systems (DES) and Renewable Energy Communities (REC) are changing the way energy systems are planned, designed, and managed. REC can play an important role in the development of green hydrogen, which can be produced in a decentralized way and used as an energy vector for various applications, such as transport and energy storage. The aim of this research is to evaluate the cost of hydrogen in distributed energy systems. The province of Taranto was chosen as a case study to model various supply scenarios for a 100 kW electrolyzer for local hydrogen production to be used within a Renewable Hydrogen Community. The results show that the optimal supply mix consists of 150 kW of photovoltaic and 100 kW of onshore wind installations, resulting in an annual hydrogen production of 7,565 kg_{H2}/yr, an excess of electrical energy produced of 27,686 kWh/yr, and a Levelized Cost of the produced Hydrogen (LCOH) of 3.82 €/kg_{H2}. The study highlights the potential use of hydrogen in different sectors, contributing to the reduction of local CO_2 emissions. Therefore, green hydrogen can contribute to creating a more flexible, decentralized, and sustainable energy system, promoting the transition to a low-carbon economy.**

Keywords*—*Hydrogen, Smart Energy Systems, Power-to-Gas, Hydrogen Valley, Integrated Energy Systems, Sector coupling

I. INTRODUCTION

The transition towards a more sustainable energy system is essential to reduce greenhouse gas emissions and mitigate climate change and represents the main transformation that societies will have to face in the coming decades [1]. This transition is not limited only to the substitution of fossil energy sources with renewable sources, but also requires a radical change in the structure and functioning of energy systems [2].

The emergence of Distributed Energy Systems (DES) and the increasing share of renewable energies are changing the way energy systems are planned, designed, and managed [3]. DES are based on the idea that they replace or complement large conventional and centralized generation plants with smaller units located near energy consumers [4], offering greater generation flexibility, reducing distribution inefficiencies and system vulnerability [5]. One of the key aspects of Distributed Energy Systems (DES) concerns the inclusion of co-generation technologies and the use of renewable sources [6]. By facilitating the integration of renewable sources through a flexible transformation system [7], DES allow the exploitation of synergies between different energy sources and vectors, responding to the needs of electricity, heating, cooling and transport demand [8].

In this context, Renewable Energy Communities (REC) are born, which were officially introduced into European legislation by the EU Directive 2018/2001, also known as the Renewable Energy Directive (RED II) [9]. They arise from the aggregation of citizens, companies, local authorities, and other territorial actors, who decide to collaborate to produce, exchange, and manage energy in a more sustainable, fair, and participatory way [10]. Energy communities can be formed by different sources of renewable energy, such as solar, wind, hydroelectric, and geothermal energy, which can be produced in a decentralized way and shared among community members [11].

REC can also play an important role in the development of green hydrogen, which can be produced in a decentralized way and used as an energy vector for various applications, such as transport and energy storage [12,13]. Energy communities could promote local green hydrogen production, share production and consumption facilities, and create innovative business models to promote the use of green hydrogen and develop a more sustainable energy system at the local and national level [14].

Among energy vectors, hydrogen has emerged as a sustainable solution for climate change, air pollution, and energy security. Green hydrogen can contribute to reducing dependence on fossil energy sources and achieving global climate goals [15]. It is an energy vector produced by water electrolysis using renewable energy, such as solar or wind energy. It has a wide range of applications that include use as a fuel (for instance transportation or power units)[16], raw material in chemical industry (for example, oil refining, fertilizer production), alternative fuel synthesis [17], direct injection into the gas network [18] and long-term energy storage solution. When hydrogen is used to store energy, it offers the possibility of being an interface between electrical, chemical, and thermal energy networks through the so-called power-to-gas process [19]. This can help balance the intermittent supply of renewable energy with demand, and therefore, facilitate and promote its development [20]. Furthermore, it can contribute to the energy system decarbonisation and to improve the energy indipendence of natural gas-based countries. This capacity makes hydrogen a valuable element to be incorporated into DES [21].

In this way, green hydrogen can contribute to creating a more flexible, decentralized, and sustainable energy system,

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in which energy production, storage, and distribution can be managed more effectively, promoting the transition to a low-carbon economy [15].

The concept of a "Renewable Hydrogen Community" (RHC) refers to a community that uses green hydrogen as a renewable energy source. This community is made up of a group of individuals, businesses, institutions, and organizations that work together to create and promote a sustainable energy system based on the use of green hydrogen.

In a RHC renewable energy is used to produce green hydrogen through water electrolysis, which is then used as an energy source for various purposes, such as electricity production, heating, cooling, and mobility. In this way, the community can reduce greenhouse gas emissions and promote the transition to a low-carbon energy system.

The aim of this research is to propose an approach to identify the optimal renewable energy source (RES) mix for decetralized hydrogen production. The Levelized Cost of Hydrogen (LCOH) is the main parameter of the analysis, in order to investigate if the hydrogen production in RHC can be a cost-effective solution. Furthermore, the research aims to assess how much hydrogen can be produced in small systems and analyse the local electricity excess of the hydrogen production system.

II. METHODOLOGY

A. Methodology Overview

To achieve the aim of this research, the province of Taranto was chosen as a case study to be analyzed. Specifically, the local production of hydrogen through 100 kW electrolyzers to be powered by various renewable energy scenarios. First, the unit production curves of onshore wind (WIND) and photovoltaic (PV) energy in the area were obtained through the PVGis software [22]. Then, the hourly production of various WIND and PV energy mixes with sizes ranging from 0 kW to 200 kW (at steps of 50 kW) of installed power were analyzed. Through an hourly analysis of the production of these mixes and using the efficiency data of the electrolyzer, it was possible to obtain the annual hydrogen production hour by hour and consequently, also the value of excess electricity produced that needs to be disposed of on the grid. Finally, an economic analysis was carried out regarding the installation and maintenance costs of the facilities used for local hydrogen production for each of the scenarios considered. In this way, it was possible to obtain and identify the levelized cost of the produced hydrogen. Annual H_2 production, electricity excess, and LCOH were compared in order to find an optimal scenario.

B. Case Study

The province of Taranto was chosen as a case study to model various supply scenarios for a 100 kW electrolyzer for local production of hydrogen to be used within RHC. To achieve this, unit production curves for PV and onshore wind power were modelled. Twenty-two scenarios were considered, involving different PV and WIND mixwith sizes ranging from 0 kW to 200 kW. Fig.1 shows the hydrogen production scheme dedicated to the RHC that was considered.

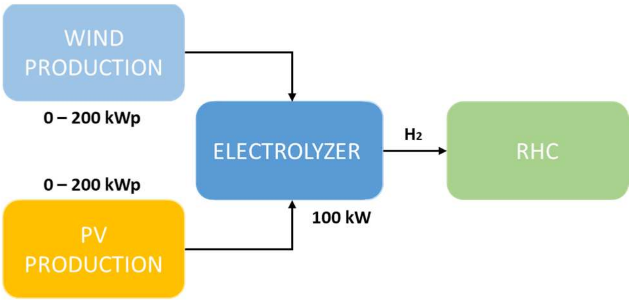

Fig. 1 Production scheme of green hydrogen that will be used by the Renewable Hydrogen Community.

To obtain the hourly production curve of PV, the PVGis software was used by entering the coordinates of Taranto, assuming a tilt angle of 35° and a south orientation. The considered panel was made of crystalline silicon with a peak power of 1 kWp. The production curves of five years were then extrapolated and averaged to obtain one curve for subsequent calculations. To obtain the production curve of WIND, a study was conducted on existing real plants (Fig.2) using information provided by the Atlaimpianti portal, managed by GSE [23].

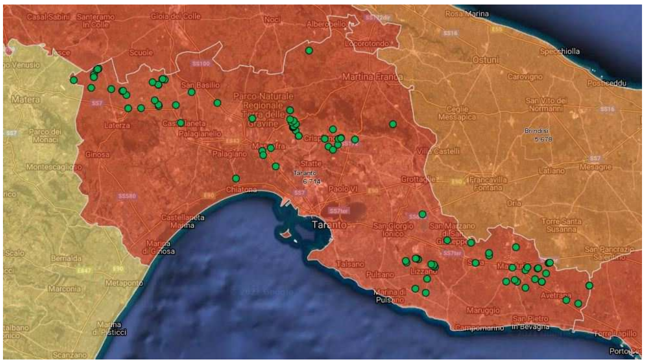

Fig. 2 Geolocation of onshore wind plants located in the territory of the province of Taranto, taken from the Atlaimpianti website [23].

Fig. 3 Identification of the 14 characteristic coordinates used for the subsequent calculation of local wind power potential.

An analysis of plant feasibility was conducted using wind data extracted from the PVGis software, evaluating overall production.

To find the unit production curve (1 kWp), an average value was taken of the production curves of these real plants, considering 14 characteristic coordinates entered as input into PVGis to reproduce the actual distribution of these plants in the territory (Fig.3).

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These unit curves of PV and wind have proven to be fundamental in analyzing various renewable energy production scenarios, which will be described below.

C. Energy and Economic Model

To find the main parameters described that were used to compare the various scenarios considered, different models were used. The energy model was implemented in MATLAB/Simulink environment.

For calculating the annual hydrogen production of a renewable mix scenario "k", the total hourly energy absorbed by the electrolyzer expressed in kWh for the k-th scenario considered was first defined.

$$E_{EL_k}(t) = min\{E_{W_k}(t) + E_{PV_k}(t); P_{EL}\} \tag{1}$$

In which:

- $E_{W_k}(t)$ is the hourly energy generated in kWh by the wind plant in scenario k.
- $E_{PV_k}(t)$ is the hourly energy generated in kWh by the photovoltaic plant in scenario k.
- P_{EL} is the installed capacity of electrolyzer expressed in kW. In this case, the same value is used for all scenarios. This value corresponds to the maximum hourly energy that the electrolyzer can absorb in kWh.

The model used to calculate the annual H_2 production by mass, expressed in kg_{H2}/yr, for each scenario k ($Prod_{H2,k}$) is:

$$Prod_{H2,k} = \sum_{t=1}^{8760} E_{EL,k}(t)/(LHV_{H2}/\eta_{EL}) \tag{2}$$

In which:

- LHV_{H2} is the lower heating value of hydrogen, expressed in kWh_e/kg_{H2}.
- η_{EL} is the electrolyzer efficiency, expressed as a percentage.

For the calculation of the excess electric energy, expressed in kWh/yr, annually produced by the renewable mix of scenario "k" considered, the following model was used:

$$E_{ECC,k} = \sum_{t=1}^{8760} max\{P_{W,k}(t) + P_{PV,k}(t) - P_{EL}; 0\} \tag{3}$$

Finally, the parameter used for the economic evaluation of the cost of hydrogen production is the LCOH, which is the ratio between the annual costs resulting from the production of hydrogen and the amount of hydrogen produced annually in the considered scenario k, expressed in €/kg_{H2}. The cost of distilled water necessary for the electrolysis process has been neglected.

$$LCOH_k = (C_{W,k} + C_{PV,k} + C_{EL})/Prod_{H2,k} \tag{4}$$

The economic analysis models for the annual costs related to hydrogen generation in each considered scenario k, expressed in €/yr, are as follows:

$$C_{W,k} = P_{W,k} \cdot (CAPEX_W \cdot crf_W + O\&M_W) \tag{5}$$

$$C_{PV,k} = P_{PV,k} \cdot (CAPEX_{PV} \cdot crf_{PV} + O\&M_{PV}) \tag{6}$$

$$C_{EL} = P_{EL} \cdot (CAPEX_{EL} \cdot crf_{EL} + O\&M_{EL}) \tag{7}$$

Where:

- $P_{W,k}$ is the installed capacity of wind power in the considered scenario expressed in kW.
- $P_{PV,k}$ is the installed capacity of photovoltaic power in the considered scenario expressed in kW.
- $CAPEX_{W/PV/EL}$ is the capital expenditure expressed in €/kW of the considered plant.
- $O\&M_{W/PV/EL}$ is the operation and maintenance cost expressed in €/kW/year of the considered plant.
- $crf_{W/PV/EL}$ is the capital recovery factor which can be computed as follows:

$$crf_{W/PV/EL} = \frac{i \cdot (1+i)^{\tau_{W/PV/EL}}}{((1+i)^{\tau_{W/PV/EL}-1})} \tag{8}$$

Here, i represents the interest rate of investments and τ is the lifetime. Calculate it for both wind turbines, PV, and electrolyzers.

D. Technical and Economic Assumptions

The assumption underlying the energy model used is that of the size of the electrolyzer, i.e., $P_{EL} = 100\,kW$. The efficiency of the electrolyzer was assumed equal to 64% [24]. The assumptions underlying the economic model used are reported in Tab.I.

TABLE I.

Type of Plant	**CAPEX [€/kW]**	**OPEX [€/kW/anno]**	**Source**
On-Shore Wind Plants	1,473	30.00	[25]
Photovoltaic Plants	995	10.00	[25]
Electrolyzers	900	13.50	[24]

Finally, the interest rate of investment was assumed equal to 3%, while other assumptions on lifetime are reported in Tab.II

TABLE II.

Type of Plant	**Lifetime of the plant, τ [yr]**	**Source**
On-Shore Wind Plants	25	[26]
Photovoltaic Plants	25	[27]
Electrolyzers	20	[24]

III. RESULTS AND DISCUSSION

To produce green hydrogen in Taranto, renewable energy sources are needed to power the electrolyzers. This requires installing renewable sources specifically for hydrogen production. In the future, excess energy generated locally could be directed to the electrolyzers, which would function as storage for renewable energy. A study analyzed 22 combinations of wind and photovoltaic plants of varying sizes (up to 200 kWp) to determine the annual hydrogen production, excess electricity, and cost of producing hydrogen. Optimal mixes of plants were sought to maximize hydrogen production and minimize excess electricity fed into the grid, considering that excess renewable energy could overload the grid and saturate the electrolyzer production. The LCOH value was a criterion for selecting the optimal production mix. An optimal mix of renewable sources was sought to be installed so that the cost of producing green hydrogen would be as competitive as possible with that of grey hydrogen produced through steam reforming, which currently varies between \$1.5 and \$3.5 per kg_{H2} [24].

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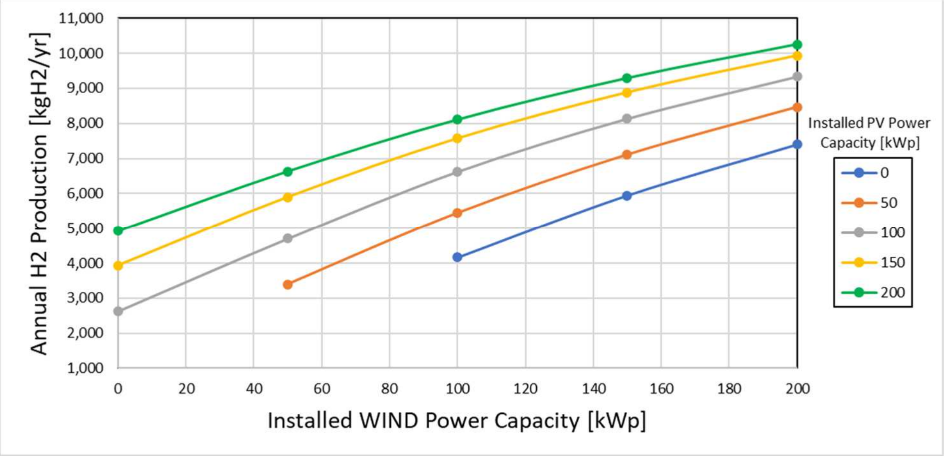

Fig. 4 Trend of the annual hydrogen production value as a function of the installed PV and WIND capacity.

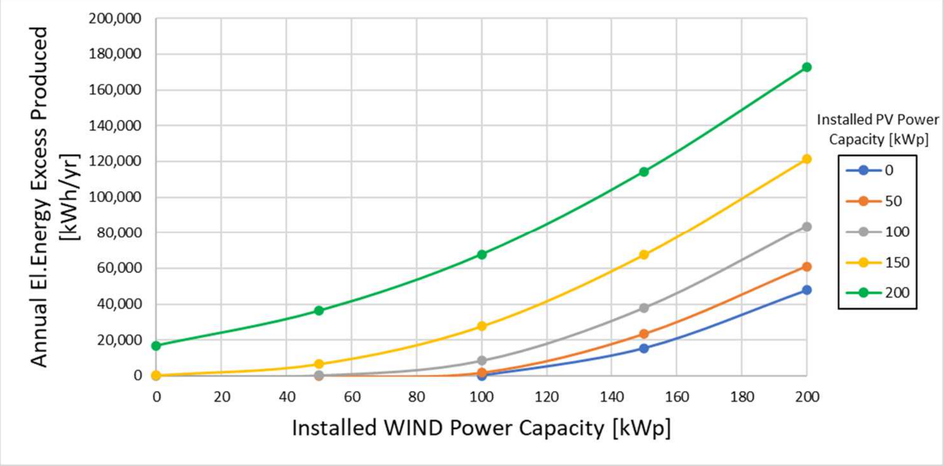

Fig. 5 Trend of the annual electricity excess production value as a function of the installed PV and WIND capacity.

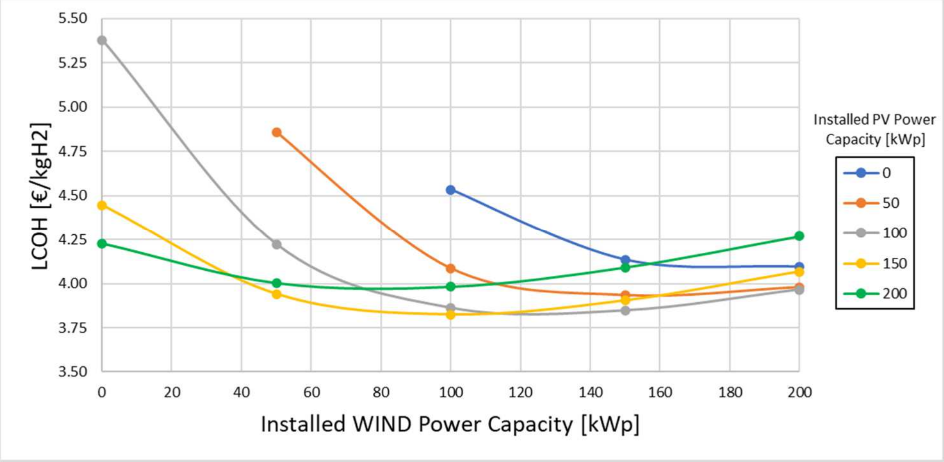

Fig. 6 Trend of the Levelized Cost of Produced Hydrogen value as a function of the installed PV and WIND capacity.

As can be seen from Fig.4 and Fig.5, hydrogen production increases as the installed renewables increase, but at the same time, excess electricity production also increases. Regarding the LCOH (Fig.6), the cost is higher in scenarios where the installed renewable power is lower, as the low hydrogen production in these scenarios has a significant impact. By increasing the installed PV and wind sizes, the cost tends to vary from 4 to 4.30 €/kg$_{H2}$.

To evaluate the optimal mix, comparative graphs were created to visually compare the outputs. In Fig.7 and Fig.8, it is possible to identify a Pareto front that allowed to identify the optimal mix scenarios, finding a compromise between the two outputs. In fact, these scenarios are located at the inflection point of these two fronts.

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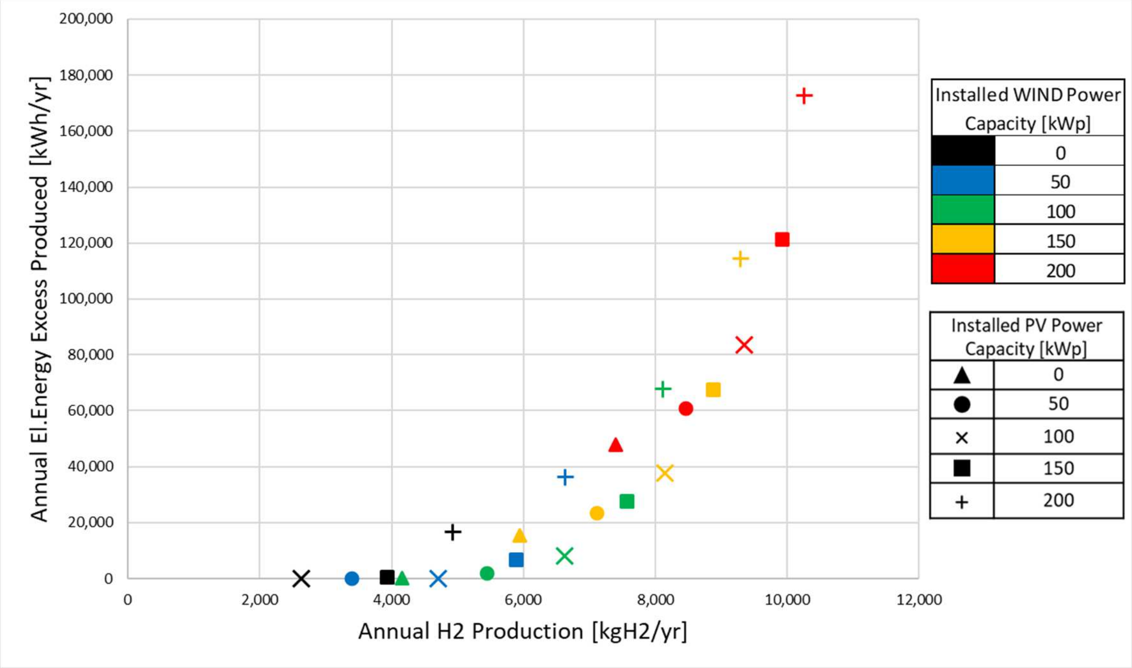

Fig. 7 Comparison between the annual hydrogen production value and the value of annual excess electricity production for each of the considered scenarios.

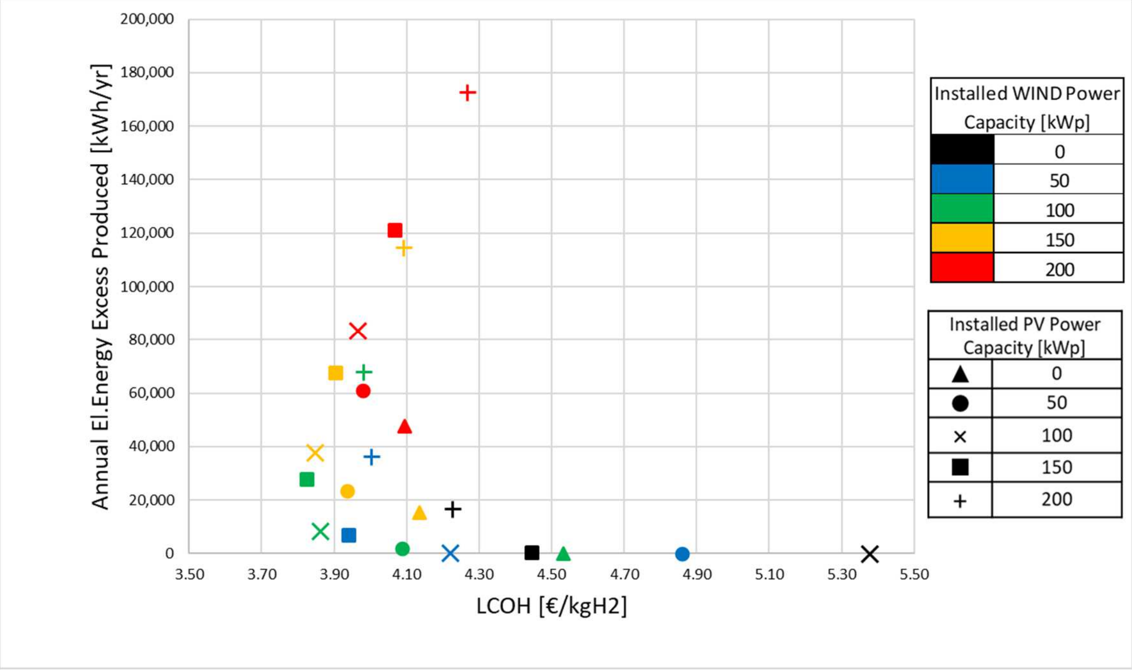

Fig. 8 Comparison between the LCOH value and the value of annual excess electricity production for each of the considered scenarios.

From the comparison of these two graphs, the optimal mix for hydrogen production in the province of Taranto, through 100 kW of electrolyzers, turns out to be the one that provides for the installation of 150 kW of photovoltaic and 100 kW of onshore wind. This was chosen as the optimal mix because it represents the scenario with the lowest LCOH, while at the same time being a good compromise between a low electricity excess value without sacrificing a good annual hydrogen production value. With this scenario, it is possible to obtain an annual hydrogen production of 7,565 kg_{H2}/year, an excess of electrical energy produced of 27,686 kWh/year and a LCOH of 3.82 €/kg_{H2}.

IV. CONCLUSION

The aim of this research is to propose an approach for identifying the optimal mix of RES for decentralized hydrogen production in a RHC. The study investigates the cost-effectiveness of hydrogen production using LCOH as the primary parameter of analysis. It also assesses the potential of small-scale systems for hydrogen production and analyzes the excess electricity generated by the system. The research highlights the potential of green hydrogen as a cost-effective solution for reducing local CO_2 emissions, promoting the transition to a sustainable and decentralized energy system.

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The optimal mix of renewable energy sources (RES) to power 100 kW electrolyzers within the province of Taranto was found to be composed of 100 kW of onshore wind and 150 kW of photovoltaic. With this mix, it is possible to predict an annual hydrogen production of 7,565 kg_{H2}/year with an excess of electrical energy of 27,686 kWh/year that must be fed back into the electrical grid. The amount of hydrogen produced can be used by the local community in various sectors, contributing to the reduction of local CO_2 emissions. The resulting LCOH for this production scenario is 3.82 €/kg_{H2}. However, the cost of producing green hydrogen is higher than that of grey hydrogen. It is important to note that the cost of grey hydrogen does not include external costs related to CO_2 emissions and other environmental and health impacts, which can have significant consequences on public health and the environment. Grey hydrogen is not a sustainable and long-term solution for global energy needs due to its negative impacts on the environment and its dependence on non-renewable fossil sources. In the future, when renewable sources have a predominant role in global energy production, it will be possible to take advantage of the excess of electricity produced by these sources, and therefore the cost of H_2 production will decrease, as it will not be necessary to install dedicated plants.

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