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Optimal RES integration for matching the Italian hydrogen strategy requirements

Antonio Sgaramella [*], Lorenzo Mario Pastore, Gianluigi Lo Basso, Livio de Santoli

Department of Astronautical, Electrical and Energy Engineering, Sapienza University of Rome, Rome, Italy

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ABSTRACT

In light of the Italian Hydrogen Roadmap goals, the 2030 national RES installation targets need to be redefined. This work aims to propose a more appropriate RES installation deployment on national scale, by matching the electrolysers capacity and the green hydrogen production goals. The adopted approach envisages the power-to-gas value chain priority for the green hydrogen production as a means of balancing system. Thus, the 2030 Italian energy system has been modelled and several RES installation scenarios have been simulated via EnergyPLAN software. The simulation outputs have been integrated with a breakdown model for the overgeneration RES share detection, in compliance with the PV dispatching priority of the Italian system. Therefore, the best installation solutions have been detected via multi-objective optimization model, based on the green hydrogen production, additional installation cost, critical energy excess along with the Levelized Cost of Hydrogen (LCOH). Higher wind technology installations provide more competitive energy and hydrogen costs. The most suitable scenarios show that the optimal LCOH and hydrogen production values, respectively equal to 3.6 €/kg and 223 kton$_{H2}$, arise from additional PV/wind installations of 35 GW on top of the national targets.

1. Introduction

The whole world is facing the big challenge to meet the growing energy demand and the decarbonization targets set by the Paris Agreement [1]. The transition towards sustainable energy systems will require a large increase in renewable energy sources (RES) in the short term, as summarized in Ref. [2]. In the last years, RES are steadily increasing and substituting the fossil fuels technologies, ensuring high quality and clean energy generation. Nevertheless, their large deployment cannot take place without changing the structure of energy systems [3]. In traditional fossil-fuel based energy systems, flexibility is provided by flexible generation capacity. When most of energy generation will be non-programmable, new strategies to provide flexibility within the system itself will need to be developed [4]. In recent years, several works have addressed that issue, concluding that system flexibility must be sought by integrating different sectors and exploiting various energy storage systems [5]. The green hydrogen production from water electrolysis allows to enhance the RES effectiveness, mitigating the photovoltaic and wind production discontinuity [6]. Thanks to its wide range of use as fuel and as renewable excess energy storage medium, hydrogen has a strong potential to address carbon neutral energy systems and link electricity and gas grids [7]. Furthermore, hydrogen can support the decarbonization of hard to abate sectors. One of the most energy-intensive and pollutant sectors is the steel segment. Approximately the release of 2.4 billion tons of CO_2, deriving from the production of 1.34 billion tons of steel, was recorded in 2019. That pollution emission corresponds to 7% of the global energy related CO_2 emission [8]. Referring to this pollution impact, the decarbonization of the primary steel production can be accomplished by means of green hydrogen-based production [9–11]. Another crucial feature for decarbonizing hard to abate sectors is represented by the transport domain, that greatly impacts on the global climates. In detail, marine transportation's emissions weight about 3%–5% of the global greenhouse gas (GHG) and this impact can grow up to 8% of GHG by 2050, if no emission reduction measures are taken [12,13]. The same goes for rail-based passenger transport and public transportation. Despite those latter can be considered among the more environmentally clean means of transportation per capita, they still impact on the global transport emission and consuming [14]. The usage of hydrogen in these segments can be crucial for achieving the Paris Agreement requirements [15–18].

The European Hydrogen Strategy [19] set electrolysers installation targets equal to 6 GW, by 2024, and up to 40 GW, by 2030, for a green

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[*] Corresponding author.
E-mail address: antonio.sgaramella@uniroma1.it (A. Sgaramella).

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hydrogen production amounting close to 10 million tons. EU member states are releasing their own strategies and the Italian Government has already set an electrolysers capacity target of 5 GW by 2030 [20]. According to that timeframe the Italian Ministry of Economic Development published the National Energy and Climate Plan (NECP) [21]. In that document the energy efficiencies, RES installations, CO_2 emission values and the sustainable mobility development are some of the main national targets that have been envisaged by 2030.

Considering national hydrogen strategies, the RES installation targets, established by the National Energy and Climate Plan, are insufficient and they need to be redefined.

The present study deals with proposing a more appropriate RES installation deployment on national scale, in order to meet the electrolysers capacity and green hydrogen production goals. The presented work has been carried out by considering the green hydrogen production as a means of balancing process, by managing and exploiting the renewable overgeneration of the system.

1.1. *Literature review*

Different authors have been investigating and developing proper methodologies for setting RES installations in energy systems, in order to achieve different goals. Sørensen [22] carried out a renewable energy and hydrogen scenario assessment for northern Europe, by applying the hydrogen technologies to both stationary energy use and transportation sector. In Sorensen's article, published in 2007, energy trade between the countries is analysed, emphasizing the benefit that intermittent RES can derive from exchange of power. Ahmad et al. [23] presented a critical analysis about potential Malaysian roadmap and milestone based on power-to-gas (PtG) approach combined with its implication on the natural gas (NG) pipeline network. Salgi et al. [24] presented a methodology for an overall energy system analysis of a hydrogen infrastructure, which meets a transportation hydrogen demand profile. The authors provided a sample scenario analysis of Western Denmark by means of Genetic Algorithms. Aditiya et al. [25] considered the prospect to institute the inter-state hydrogen energy system on selected countries in Asia-Pacific region, by means of four indicators based on domestic energy capacity, national wealth, society development, and research and development (R&D). Child et al. [26] investigated on the feasibility of the 2050 Finnish energy system based on 100% renewable energy, in accordance with P2G strategies. The authors computed different installation scenarios, employing EnergyPLAN software. Welder et al. [27] determined the cost-optimal design and operation of future energy systems for Power-to-Gas scenarios in Germany. In the simulated scenarios the generation, transmission and storage have been assigned to onshore wind turbines, hydrogen pipelines and underground storage facilities, respectively. In that assessment hydrogen is aimed to mobility and industry. Frischmuth et al. [28] analysed the EU strategies' individual and combined effects, for the EU energy systems neutrality achievement. In their analysis the authors highlighted the hydrogen key-role in the future European energy system. Hydrogen results crucial in different power sector coupling and the different cross-sectional applications deployment enables the reduction of the overall energy system cost and generating power unit cost as well. Partidário et al. [29] assessed the hydrogen production sustainability and the end use within the PtG value chain, by strongly focusing on heating applications. This work has been carried out in the light of the Portuguese Roadmap for H_2. Irawan et al. [30] performed a multi-objective optimization method for investigating national/regional power generation expansion planning in the case of stochastic electricity demand. Reyes-Barquet et al. [31] presented a multi-objective optimal design of a hydrogen supply chain networks in Mexico. In their study the authors aimed to evaluate the economic and environmental benefits owed to the deployment of biomass wasted for energy generation and its integration to the national energy grid. The optimal hydrogen supply chain network configuration selection was identified via a multi-objective optimization tool, as the genetic algorithm, and by means of a multi-criteria decision technique like TOPSIS. For the optimization criteria the authors addressed the problem as a mixed-integer linear program (MILP). The latter approach was also adopted by Liu J. et al. [32] in their paper, in order to minimize the annual capital and operation cost of their system. The authors analysed different energy demand profiles and solar radiations in twelve typical cities in the world for the optimal planning evaluation of distributed hydrogen-based multi-energy systems. Jiang H. et al. [33] investigated the planning coordination between the power system generation and transmission as well as hydrogen supply chain with transportable hydrogen storage. The study shows that the planning coordination can reduce and better manage the RES curtailment ratio. Moreover, the deployment of hydrogen also allows operation cost saving.

The literature that concerns the hydrogen energy planning is quite small and fragmented. At the best of authors' knowledge, studies dealing with the RES quantification and planning, targeted towards the hydrogen goals compliance, do not exist. Furthermore, the energy planning is a complex issue concerning different energy, environmental and economic aspects and just a few works in literature proposed a method integrating multi-objective optimization for choosing the best configuration.

Therefore, the authors deem to contribute to the know-how on this topic, by providing a methodological approach for merging the hydrogen energy planning with national energy strategies by investigating how the RES installation targets can be affected by the hydrogen value-chain development.

1.2. *Scope of the article*

The purpose of this work is to propose an approach for improving national energy and climate plans in the light of the new electrolyser targets set by the national hydrogen strategies. Indeed, the hydrogen energy planning cannot be assessed as a single issue, but it must be carried out by analysing the role of hydrogen in the whole energy system.

The proposed approach is applied to the Italian energy system as a case study, taking into account the current national energy strategy and the new targets for the electrolyser installation. This paper aims at identifying the optimal additional RES installation targets in the Italian energy system which are needed for accomplishing the hydrogen value-chain deployment.

The hydrogen energy planning requires to analyse different aspects for determining the optimal energy system configuration. Therefore, the assessment of several issues turns out to be of utmost importance in the planning process. In the present study, a multi-objective optimization model of the yearly hydrogen production, critical energy excess production, levelized cost of hydrogen (LCOH) and total investment costs analysis has been proposed. The targets of both PV and Wind installations have been raised according to the additional flexibility provided by the electrolysers. Finally, according to the proposed methodology, the best configuration has been detected.

2. Methodology

As aforementioned, the main aim of this study is to draw up a method for the RES implementation in the Italian Energy system, in order to achieve the hydrogen targets, envisaged in the National Hydrogen Guidelines. For that purpose, a preliminary evaluation on the overall 2030 energy demand and supply has been carried out, considering the NECP's targets, the future energy trends, and roadmaps. All of data related to the analysed energy system, including RES installations and 5 GW of electrolysers capacity, have been processed by means of EnergyPLAN [34]. In that calculation environment, the Italian energy system forecast to 2030 by the Italian NECP has been modelled and validated. Electrolysers have been implemented for exploiting renewable energy over-generation, hailing from the difference between the energy supply and the energy demand, so as to produce a real green hydrogen.

The detection of the most suitable scenarios for the 2030 Italian energy system has been investigated by iterating the photovoltaic and wind capacity.

EnergyPLAN ensures energy balance hourly analysis, also providing the total over-generation amount useful for driving the electrolysers as well as the RES excess value. The following subdivision of those two outputs, sorted by renewable sources, has been performed by a model complying with the PV dispatching priority.

Those data, along with the yearly average CAPEX evaluation related to PV plants and wind farms in Italy, have been used for assessing the Levelized Cost of Energy (LCOE). In such a way, the LCOE is dependent on the outputs of the energy simulations. Furthermore, the Levelized Cost of Hydrogen (LCOH) has been computed, by taking in account the electrolysers' CAPEX and O&M cost and the yearly hydrogen production as well. Different PV/wind capacity combinations have been simulated and compared each other, in order to identify the optimal breakdowns of those additional RES.

That strategy has been employed for several iterative scenarios. Thereafter, the best installation solutions have been detected by means of a multi-objective optimization model based on Pareto fronts. The Utopia point identification allows to determine the most suitable scenario for this assessment. Lastly, a sensitivity analysis has been performed for the five optimal scenarios. The logical pathway associated to the applied methodology has been graphically outlined showing the calculation flows, as reported in Fig. 1.

2.1. *EnergyPLAN*

The energy balances computation related to the different electrical systems has been performed via dynamic systems by means of the EnergyPLAN software [34]. That tool offers a fundamental holistic approach and assists in large scale energy planning strategies design. Furthermore, the software envisages technical and economic analyses, resulting from different strategies and investments. EnergyPLAN solves the energy balance equations, requiring as input values the energy demand, the energy production, and the simulation approach. The first input value mainly consists of electricity and heat demand, deriving from buildings and industry, and of transport demand as well. The supply part comprises all the energy production technologies, also including the energy conversion units as electrolysers, gasification plants and biogas as well as hydrogenation units. Input and output values of that software are depicted in the Fig. 2. EnergyPLAN allows to apply different strategies for the analysis processing, by choosing between technical or economic approach. The most suitable strategy for this assessment is a technical approach, which ensures the electrical generation enhancement as a function of both thermal and electrical demand. The minimisation of electrical export values is thereby envisaged. On the other hand, the 2030 Italian import energy values have been foreseen by NECP's targets. So, once those values have been entered, the hourly energy over-generation has been managed by prioritizing the electrolysers. Those latter exploit the occurring over-generation, providing the total hydrogen production. The excess management is a critical aspect for properly assessing the green hydrogen production.

2.2. *Reference scenario*

The 2030 Italian reference scenario, based on the Italian NECP-2019, has been shaped starting from the existing 2017 EnergyPLAN model [35]. This latter represents the 2017 Italian energy system, which was developed by Bellocchi and Manno and it was used in different works [36–38].

That model has been updated also in order to assess decarbonization strategies of the Italian energy systems by 2030 and more details about the technical and economic model parameters are available in Ref. [39]. Herein a brief description of the EnergyPLAN model and the main values for model validation.

Hourly demand and supply distributions have been entered in the software, as it works with hourly steps. The Bellocchi and Manno model provided the energy distribution for the Italian Energy System. The 2030 reference scenario has been built complying with the NECP's targets. Nevertheless, it does not provide all the input data which are needed for the overall 2030 Italian energy system modelling. Therefore, some data have been picked out from other sources and some assumptions have been made. Finally, the system has been validated by comparing the model's outputs and the main NECP targets, including notably the RES targets, listed in Table 1. The biggest estimated mismatch amounts to 1.26% relative to the avoided $CO_{2,eq}$ emission value. That one is lightly underestimated, exception for the total primary energy consumption, fossil fuels consumption and RES generation, which are slightly overestimated instead. All the discrepancy values have been shown in Table 2.

Finally, as the values mismatch is insubstantial, the modelled 2030 Italian energy system has been considered validated.

2.3. *Overgeneration pattern model*

The current breakdown model attempts to evaluate the overgeneration impact on the green hydrogen production in energy and economic terms. EnergyPLAN provides both the overgeneration share exploited by the electrolysers (ELT) and the critical excess energy production (CEEP). Those two outputs have been shared into photovoltaic and wind sources, accounting for the dispatching priority of PV production in Italian energy system. In the hours when the overgeneration value is equal to zero, all the renewable energy generation meets the energy demand. On the other hand, in some hours the total overgeneration is utilized by the electrolysers for the water splitting process. Hence, if ELT values are lower than wind energy generation, the whole

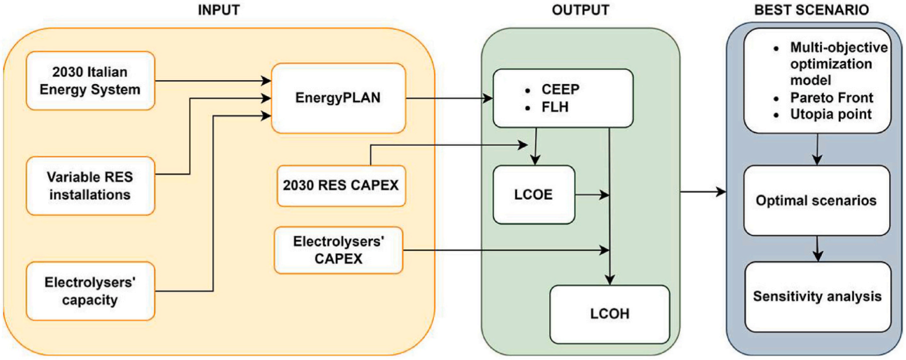

Fig. 1. Methodology graphical outline.

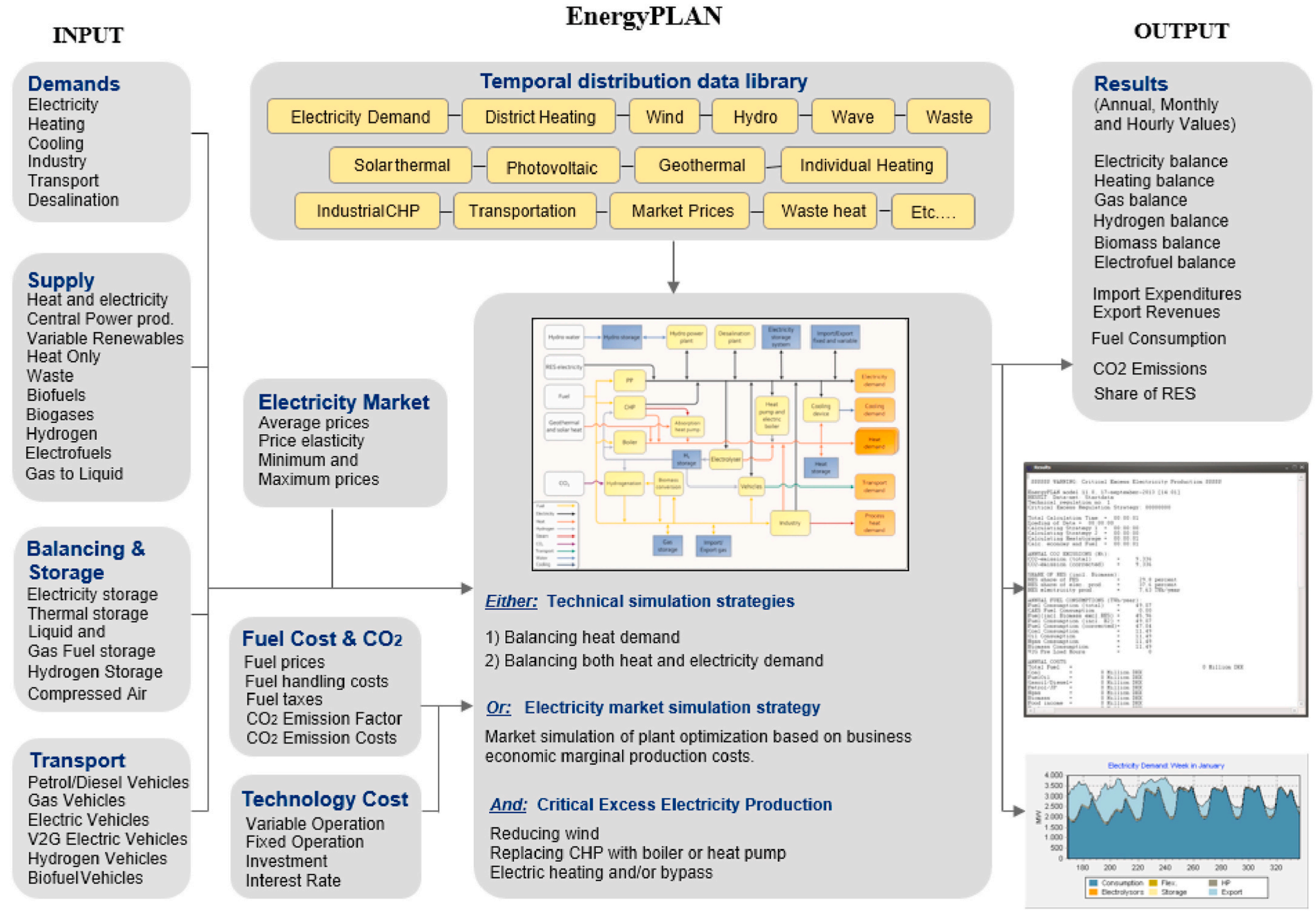

Fig. 2. EnergyPLAN data inputs and outputs [34].

Table 1
Electricity RES targets of Italian NECP by 2030.

2030 Targets	Capacity (MW)	Energy (TWh)
Hydroelectric	19,200	49.3
Geothermal	950	7.1
Wind	19,300	39.11
of which Off-Shore	900	2.39
Bioenergy	3760	15.7
PV	52,000	72.31

Table 2
Comparison between EnergyPLAN model and Italian NECP targets.

Value	Unit	NECP - 2019	EnergyPLAN model	Discrepancy %
Annual CO_{2eq} emissions	Mt/yr	256	252.8	−1.26%
Primary Energy Supply	TWh/yr	1355.4	1357.6	+0.16%
Coal	TWh/yr	32.7	32.8	+0.20%
Oil	TWh/yr	390.7	391.6	+0.21%
NG	TWh/yr	568.9	568.7	−0.03%
RES	TWh/yr	429.4	430.8	+0.34%
Electricity by RES	TWh/yr	186.8	187.3	+0.28%

amount of energy used by the electrolyser derives from wind source. Otherwise, when the energy used by electrolysers is higher than wind energy production, a share of ELT derives from wind sources and the remaining part from PV generation, according to the dispatching priority. In the last-mentioned cases, the CEEP value is equal to zero. Notwithstanding, in some hours the overgeneration is not entirely utilized for water electrolysis. As for the ELT values, also for the CEEP the model provides the excess sharing amount by photovoltaic and wind sources. When the total overgeneration (ELT + CEEP) results higher than wind energy generation, a further distinction has been made:

- If the total overgeneration is larger than the hourly wind generation, then the latter results as CEEP; the total amount of energy exploited by electrolysers comes from photovoltaic generation and finally the residual part of critical excess energy production is due to the remaining PV overgeneration. This scenario typically reflects the summer case, because of the high PV generation.
- Otherwise, if the total overgeneration is lower than the hourly wind energy production, then the total CEEP comes from wind sources, the remaining wind generation is exploited by the electrolysers, and the residual ELT energy hails from PV generation. This is the most frequent scenario occurring over the very windy hours.

This model has been more clearly shown in the Fig. 3, in which it is depicted a flow chart with the hourly analysis for the ELT and CEEP subdivision by renewable sources.

Where:

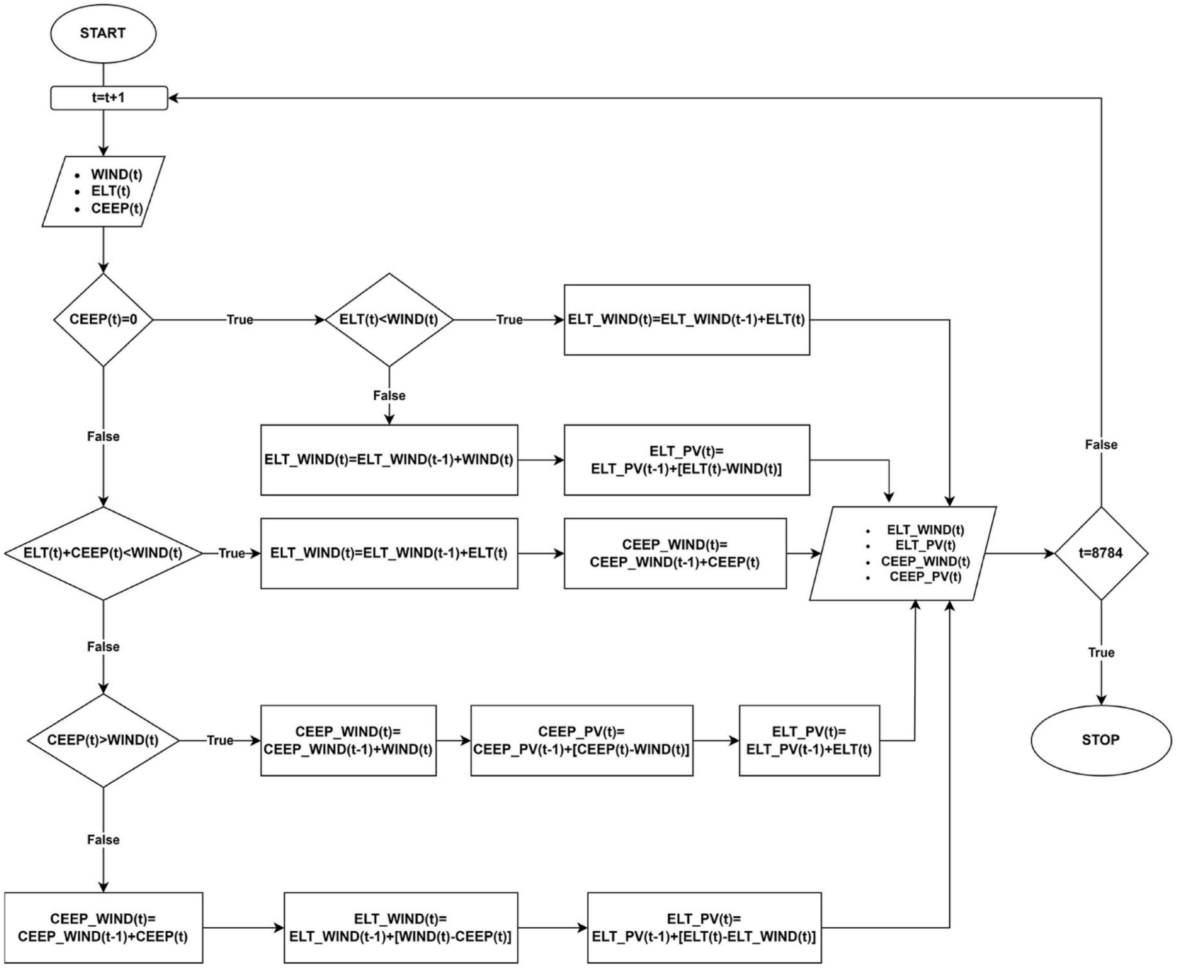

Fig. 3. Flow chart for the overgeneration subdivision.

- ELT_wind: wind over-generation used by electrolysers.
- ELT_PV: photovoltaic over-generation used by electrolysers.
- CEEP_wind: wind excess energy not exploited by electrolysers.
- CEEP_PV: photovoltaic excess energy not exploited by electrolysers.

The outcomes of this breakdown model are of utmost importance for the correct LCOE evaluation. That parameter takes into account only the effective energy generation meeting the system energy demand and the electrolysers' capacity. As a result, the hourly CEEP value negatively affects the LCOE associated to the single technology and of the system as well. That effect is reported in the Equation (3).

That analysis has been performed for the 8784 h of the year. Finally, by adding up the outcomes, the total yearly overgeneration shares by sources have been obtained for each scenario.

2.4. Calculation methodology

One of the main outcomes for the most suitable scenarios pursuit so as to get to the National Hydrogen targets, is the levelized cost of hydrogen (LCOH) production [40]. That indicator takes into account the electrolysers' capacity, the renewable energy used for feeding the water electrolysis process and the total hydrogen production, as shown in the Equation (1):

$$LCOH = \frac{crf * CAPEX + OPEX}{m_{H_2}} \tag{1}$$

Where:

- LCOH: levelized cost of hydrogen [$€/kg_{H2}$].
- crf: capital recovery factor.
- CAPEX: capital expenditure for the purchase of electrolysers [€].
- OPEX: operation and maintenance costs for electrolysers [€/yr].
- m_{H_2}: hydrogen production [kg].

The capital recovery factor (crf) reads as follows:

$$crf = \frac{i * (1+i)^n}{(1+i)^n - 1} \tag{2}$$

Where:

- n: plant lifetime.
- i: nominal discount rate, which has been considered equal to 3%.

Essentially the LCOH method is based on the levelized cost of energy (LCOE) calculation procedure [41]. Indeed, it is mostly used for estimating the green hydrogen production, since the renewable technologies are widely used. LCOE values related to photovoltaics, wind, and their mix, have been used for calculating the electricity cost in the different installation scenarios.

$$LCOE_i = \frac{crf * CAPEX_i + OPEX_i}{KWh_i} \tag{3}$$

Levelized cost of energy hailing from each green technology is necessary to calculate the final LCOE values affecting the green hydrogen production cost.

$$LCOE_{to\ ELT} = \frac{kWh_{PVtoH2} * LCOE_{PV} + kWh_{WINDtoH2} * LCOE_{WIND}}{kWh_{REStoH2}} \tag{4}$$

Where:

- KWh_{PVtoH_2}: PV total energy used by electrolysers.
- $KWh_{WINDtoH_2}$: wind total energy used by electrolysers.
- KWh_{REStoH_2}: total renewable energy exploited by electrolysers.
- $LCOE_{WIND}$: total LCOE derived from on-shore e off-shore wind technology.
- $LCOE_{PV}$: total LCOE derived from PV technology.

That value is also required for calculating the operational cost associated to the renewable hydrogen production according to the Equation (5):

$$OPEX_{H_2} = C_{O\&M} + C_{el} * 5\ GW \tag{5}$$

C_{el} has been calculated by multiplying the renewable electricity cost, used by the electrolysers, and their full load hours (see the Equation (6)):

$$C_{el} = LCOE * FLH_{elt} \tag{6}$$

The total amount of produced hydrogen is directly proportional to the energy used for the water splitting reaction and to the electrolyser efficiency as well, as reported in the Equation (7):

$$m_{H_2} = E_{elt} * \frac{\eta_{elt}}{LHV_{H_2}} \tag{7}$$

Where η_{elt} is the efficiency of the electrolyser and LHV_{H_2} stands for the lower heating value of the H_2.Best scenario detection

The 2030 NECP installation scenario appears not aligned with the National Hydrogen guidelines. Indeed, the resulting electrical overgeneration consumed by the electrolysers turns out to be very small and it is not enough for accomplishing the Italian Hydrogen Roadmap's targets.

Therefore, new scenarios have been simulated by applying an iterative process on the additional photovoltaic and wind capacity to be installed. In so doing, the ideal hydrogen production configuration, matching the Italian targets, can be identified. The other parameters, dealing with the foreseen energy demand, the transport sector, and the other technologies for the energy supply, have been unaltered. In order to generate the optimal scenarios population, the additional capacity to the NECP PV and wind installations have been linearly increased by 5 GW steps.

2.4.1. Multi-objective optimization model

In this assessment, the most suitable RES installation scenarios have been detected by means of a Pareto-based multi-objective optimal criteria. This approach allows to better understand the overall system and to recognize a set of ideal trade-off wind and PV installations among the analysed scenarios. This tracking process has been performed through a Pareto front. According to the literature [42–44], the multi-objective problem can be mathematically addressed as follows:

$$minimize : y = f\ (x) = (f_1(x), f_2(x), ..., f_k(x)) \tag{8}$$

$$subject\ to : g(x) = (g_1(x), g_2(x), \ldots, g_m(x)) \leqslant 0$$

$$h(x) = \left(h_1(x), h_2(x), \ldots, h_p(x)\right) = 0$$

$$l_i \leqslant x_i \leqslant u_i, i = 1, 2, ..., n$$

$$where : x = (x_1, x_2, ..., x_n) \in X$$

$$y = (y_1, y_2, ..., y_k) \in Y$$

In this configuration x denotes the iterated parameters of the n decision variables. Those vectors are listed into a bounded range by lower and upper limits of the *i-th* variable, which are identified with l_i and u_i, respectively. The overall vector of k objective functions is associated to y. This latter is a member of the objective space, denoted with Y. On the other hand, X represents the decision space, made up of the whole amount of x vectors. *g(x)* represents a set of inequality constraints with feasible solutions. *h(x)* indicates the set of p equality constraints. The configurations pursuit is based on a trade-off of yearly hydrogen production, critical energy excess production, LCOH values and total investment costs.

The x values, that meet the Equation (8) requirements, create feasible solutions set. In this set some x Pareto solutions dominate other candidate parameters $x^{'}$. Such dominance rule is regulated as follows:

$$\begin{cases} f_i(x) \leq f_i(x'), \forall i \in \{1, 2, \cdots, m\} \\ f_i(x) \ < \ f_i(x'), \exists i \in \{1, 2, \cdots, m\} \end{cases} \tag{9}$$

The not dominated Pareto solutions outline the Pareto front. Each Pareto scenario represents a solution that cannot be improved in one of the objectives without negatively affecting another objective. The scenarios delineated in the Pareto front represent the potential optimal scenarios for the assessment.

Finally, in order to address the most suitable scenario evaluation on the Pareto front, the Utopia point (UP) has been detected. This latter represents an ideal but unfeasible solution, that meets the best requirements for a scenario. Specifically, considering a two-objective minimisation problem, the UP is a point whose abscissa is associated to the best value accounted on the y-axis and as ordinate the best value presented on the x-axis. The Utopia point represents a mathematical expedient for detecting the best point in the Pareto front. Indeed, the solution characterised by the minimal distance from the UP denotes the most suitable scenario, as shown in the following equations [44–46].

$$\min(P_{solution}) \tag{10}$$

$$P_{solution} = \sqrt{\sum_j \left(f_{jUtopia} - f_j\right)^2} \tag{11}$$

Where $P_{solution}$ is the distance between the normalized objective j function and the detected Utopia point; $f_{jUtopia}$ represents the allowed minimum value of normalized objective function j. On the other hand, f_j is the non-minimum possible value of normalized objective function j.

2.5. Technical and economic assumptions

The energy and economic assumptions to perform all of calculations have been summarized in Table 3. The values described in Table 3 represent the economic and performance benchmark values of electrolysers, PV, and wind technologies. In detail, efficiency, CAPEX, lifetime and operation and maintenance (O&M) costs have been reported. As regards PV and wind CAPEX, a detailed discussion has been provided in Section 2.7. Data have been detected in literature for the computation of the LCOH and LCOE values in the designed 2030 Italian energy systems, according to Equations (1) and (3) respectively.

Table 3
Energy and economic assumptions.

Technology	Data	Value	Unit	Reference
Electrolyser	η	69	%	[47–50]
Electrolyser	CAPEX	450	€/kW	[47,48,50–54]
Electrolyser	O&M costs	CAPEX*1.5%	€/kW	[47,50,53,54]
Electrolyser	Lifetime	15	years	[47,49,52,53]
PV	O&M costs	15.4	€/kW	[55–58]
PV	Lifetime	25	years	[55–58]
Wind	O&M costs	37.8	€/kW	[56,58–60]
Wind	Lifetime	25	years	[58,60]

2.6. RES CAPEX assessment

In a framework where the green hydrogen production derives from PV and wind over-generation, the correct forecast of the renewable LCOE is of utmost importance for properly estimating the LCOH. The actual renewable energy cost depends on the RES plants installation timing. Indeed, the CAPEX of renewable technologies is continuously decreasing, and that trend needs to be taken into account when calculating the national average LCOE. For that purpose, the present work investigates the Italian yearly trend costs of utility-scale, referred to the assumed renewable mix technologies. In so doing, it is possible to define the cumulative capital expenditure, to effectively implement the hydrogen strategy. Recent market trends report a PV installation growth by 2019 up to 580 GW, equal to fourteen times the 2010 installation. The 60% of that amount is installed in Asia. That installation growth is mostly correlated to a significant PV technologies maturity as well as to a cost reduction up to 90% in some countries, as depicted in Fig. 4. From the IRENA study [61] merges how, nowadays in Italy, the photovoltaic installations cost is among the lowest. Herein the total PV installation costs by 2030 have been analysed for deducing the PV LCOE over the projection horizon [62].

As depicted in Fig. 4, owing to a higher efficiency in the modules production process, the market price of PV technologies has significantly decreased in the last years, achieving very competitive prices. The model foresees a further cost reduction of PV technologies by 2030 with an asymptotic decreasing trend. On the other hand, the cost trend of Italian wind technologies is characterised by an oscillating curve over the years, as shown in Fig. 5. The installation costs attained very competitive levels in the years 2000–2002, after which the prices soared, due to the raw materials costs rising, new technologies' introduction, and consequently, to the supply chain bottlenecks. The cost peak values were achieved in 2007–2010, thereafter a significant lessening was recorded.

As regards the CAPEX assessment, PV and wind installations have been detected and analysed in a time span of 25 years, by following the NECP's capacity targets. The RES capacity trendlines have been plotted in Fig. 6.

Both PV and wind installed capacity have been extrapolated from the TERNA database [63] and from the NECP document. Yet, the PV and wind capacities have been iterated, in order to detect the most suitable CAPEX values for the energy and economic analysis of this work.

The CAPEX calculation has been performed by considering the PV and wind plants lifetime approximately equal to 25 years. However, that value appears to be overestimated for the PV especially considering the modules installed in 2005. Therefore, the technologies deployed before 2010 have been assumed as installed in 2030, in addition to the new capacity targets. The CAPEX values for the 2030 simulated scenarios have been computed as follows:

$$\overline{C_t} = \frac{\sum_{i=2010}^{t} P_i * C_i}{\sum_{i=2010}^{t} P_i} \tag{12}$$

Where:

- $\overline{C_t}$: average installation cost at the reference year "t" [€/kW]
- C_i: installation cost at "i"-year [kW]
- P_i: power capacity at "i"-year [€/kW]

3. Results and discussion

In this section, the outcomes of this analysis have been presented and discussed. At first, the simulation has been performed with the foreseen 2030 Italian energy demand and energy supply, also including the PV and wind capacity values, outlined by the NECP. Those values are respectively equal to 52 GW and 19.3 GW. Thus, by means of the aforementioned overgeneration management system, the resulting electrolysers' full load hours amount to 771 h per year, ensuring a minimal green hydrogen production of 79.86 thousand tons and the LCOH piling up to 5.955 $€/kg_{H_2}$. Because of the PV and wind capacities' inadequacy, some simulations have been performed by following the model for the energy and economic analysis related to the 2030 Italian energy system. In detail, nine additional photovoltaic settings and nine additional wind capacity scenarios have been analysed to evaluate, case-by-case, the resulting green hydrogen production, the critical excess energy generation and the levelized cost of renewable energy for the LCOH assessment.

3.1. Hydrogen production

In order to evaluate the photovoltaic and wind additional capacity suitability on the foreseen Italian energy system, a preliminary analysis on the state of the art of electrolysers and RES technologies has been carried out. In Table 3, all of parameters used for calculations are outlined.

Growing RES installations lead to energy production increase and consequently to electrolysers' full load hours enhancement. Fig. 7 shows the rising trend of green hydrogen production, owed to the renewable overgeneration exploitation. In detail, a steeper rising trend occurs at the abscissa corresponding to 10–15 GW of additional wind installation.

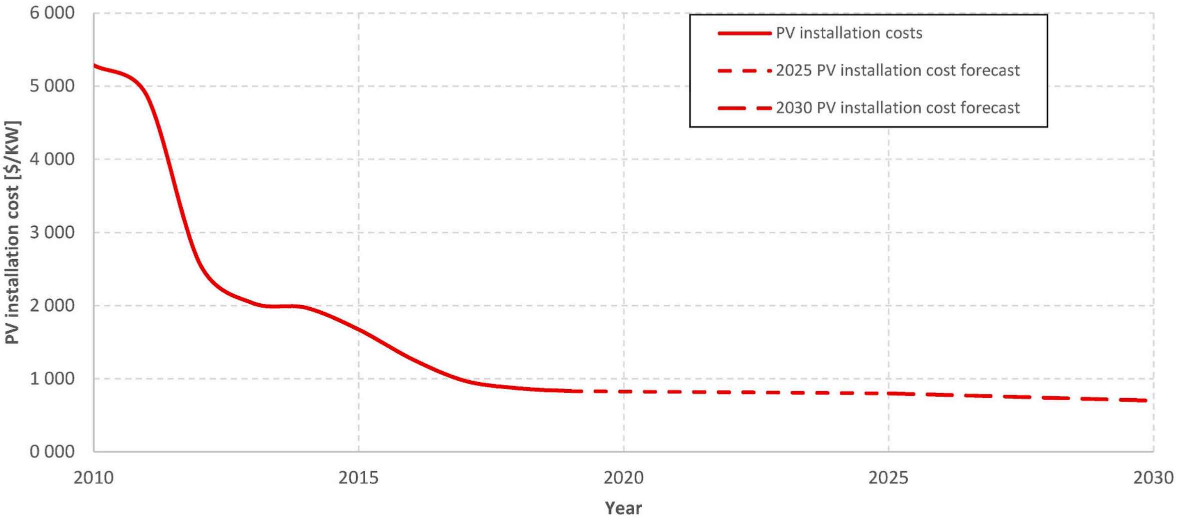

Fig. 4. Italian PV installation costs 2009–2030.

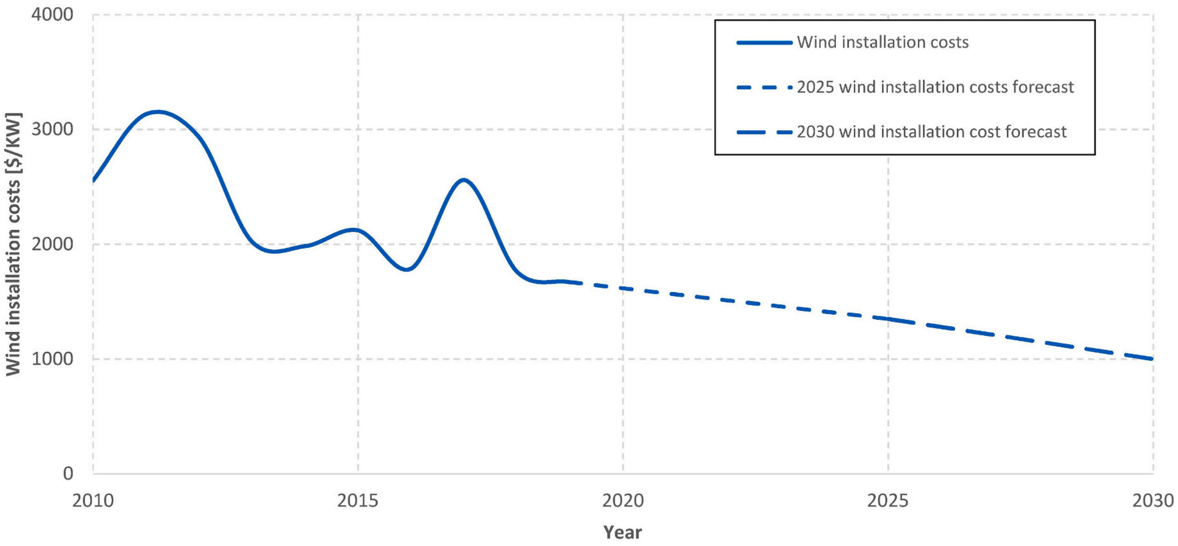

Fig. 5. Italian wind installation costs, 2009–2030.

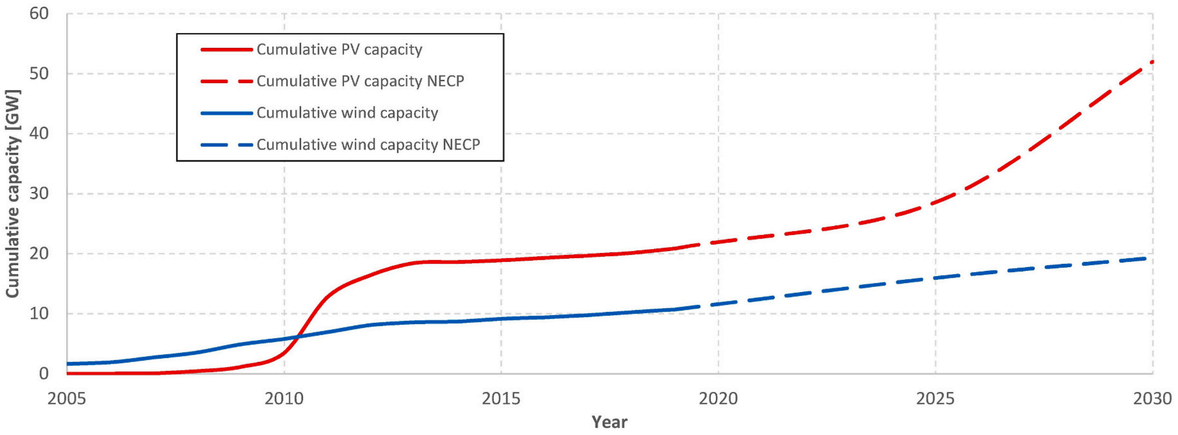

Fig. 6. PV and wind installations, 2005–2030.

That development is attributable to the PV dispatch priority in the Italian energy system and to the ensuing wind overgeneration, exploited by the electrolysers. A more significant hydrogen production growth occurs at greater wind additional capacity. Specifically, an additional installation of 40 GW of wind power leads to electrolysers' full load hours up to over 4 times higher than the achievable ones matching the NECP installation targets.

3.2. Critical RES excess

Even though the increasing RES capacity extends the electrolysers' full load hours, it also entails a critical excess of energy production that neither the electrolysers can offtake, since their capacity is not increased as much as the released energy. The CEEP shows double drawback: the former deals with the LCOH value break down, while the latter subjects the electrical grid to further stress and potential failures. In the foreseen 2030 Italian energy system, as the electrical overgeneration is a limited amount, the CEEP value is equal to only 0.7 TWh. The increasing trend of the critical excess energy production, deriving from the additional RES installation, is illustrated in Fig. 8.

By analysing the outcomes, it emerges how higher PV critical excess energy generations occur at greater wind capacity values, although photovoltaic generation benefits from dispatching priority. It is noteworthy that the boost of trend is valuable at higher additional PV capacity. Indeed, by increasing 40 GW of PV and no adding wind farms, more than 20 GW of CEEP is registered. Differently, by adding 40 GW of wind capacity and no additional PV, the foreseen CEEP value amounts to slightly over 15 GW. This phenomenon is attributable to the storage systems in the Italian system, such as centralized electric batteries and hydroelectric pumping, whose capacities do not respect the PV dispatching priority. On the other hand, higher PV capacities enhance the CEEP values deriving from the wind farms as well, due to the dispatching priority. Nevertheless, the latter's increasing trend is more subdued than the PV enhance impact.

3.3. LCOH

The most relevant benchmark for the LCOH evaluation is the levelized cost of the renewable energy, exploited by the electrolysers, for the green hydrogen production. The LCOH reduction trend, coming out from the simulated RES scenario, is depicted in Fig. 9.

The photovoltaic LCOE value shows a rapid decrease as the capacity increases. Yet, when further 15–20 GW are added on the top of the 52 GW, which have been enshrined by the NECP, the trend stabilizes on a generation cost close to 65.50 €/MWh. That asymptotic behaviour is due to the resulting CEEP values. That trend is also ascertained for the LCOH plot in Fig. 9. Moreover, the wind LCOE curve reaches a minimum close to the additional 20–25 GW. Beyond that value the LCOE reverses the

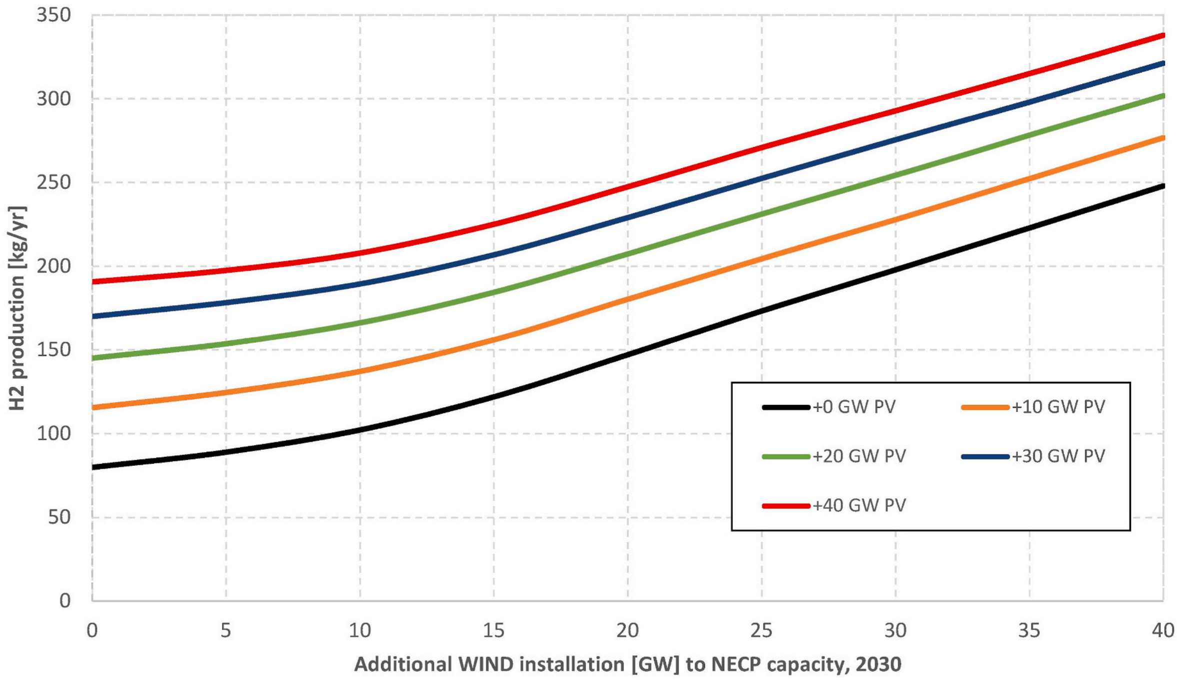

Fig. 7. H_2 production trend as wind capacity increases.

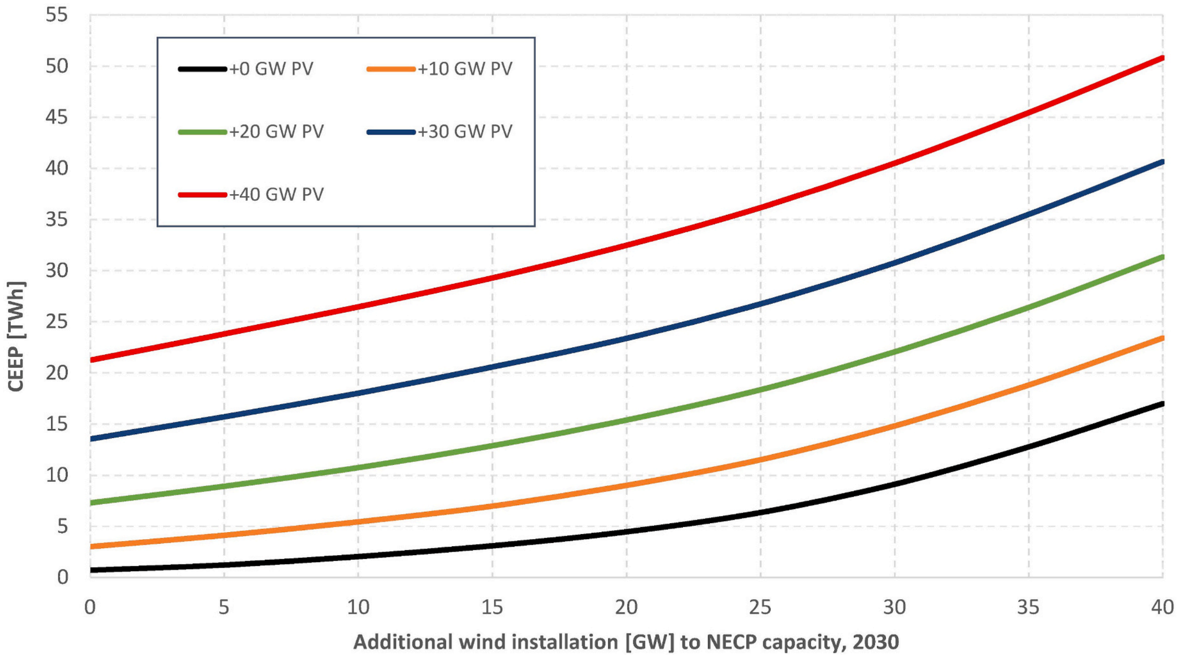

Fig. 8. CEEP trend as wind capacity increases.

decreasing trend, due to the PV dispatching priority. The analysis of the other installations' scenarios shows that the lowest levelized cost of renewable energy, used in the electrolysis process, occurs at the additional PV and wind capacity equal to 0 GW and 30 GW, respectively. That scenario explicitly indicates the further addition of photovoltaic installations is not very suitable in terms of economic competitiveness of green hydrogen production. The most suitable RES installation scenarios cannot be investigated by maximising only the green hydrogen capability, but even accounting for CEEP and CAPEX values, in order to exploit the overgeneration as much as possible. Fig. 10 shows the LCOH, CEEP and the hydrogen production trends in the scenario corresponding to 52 GW PV capacity and increasing wind installations. Once the 20–25 GW additional wind capacity is considered, the CEEP curve grows exponentially, which negatively affects the LCOH slope. Indeed, after the threshold value of 23 additional GW, the LCOH curve tends to decrease in a stepwise fashion almost asymptotically, providing more balancing stress to the grid.

3.4. *Optimal scenarios identification*

As mentioned above, the most suitable PV and wind capacity settings, that address the 2030 Italian Hydrogen Roadmaps goals

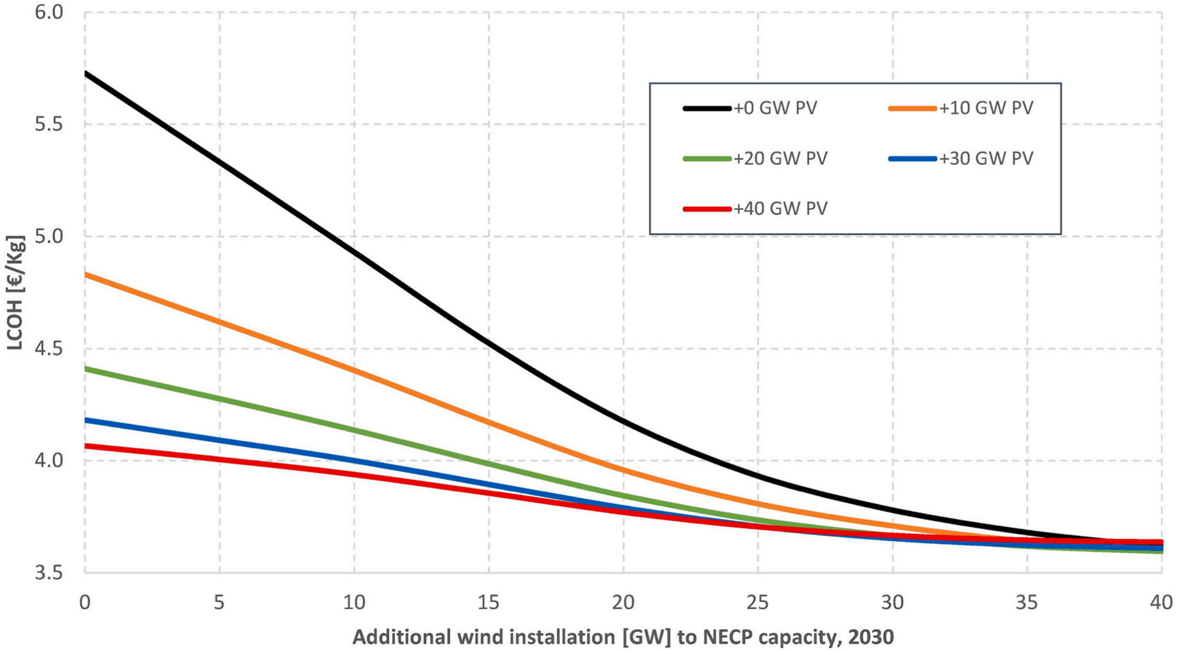

Fig. 9. LCOH trend as wind capacity increases.

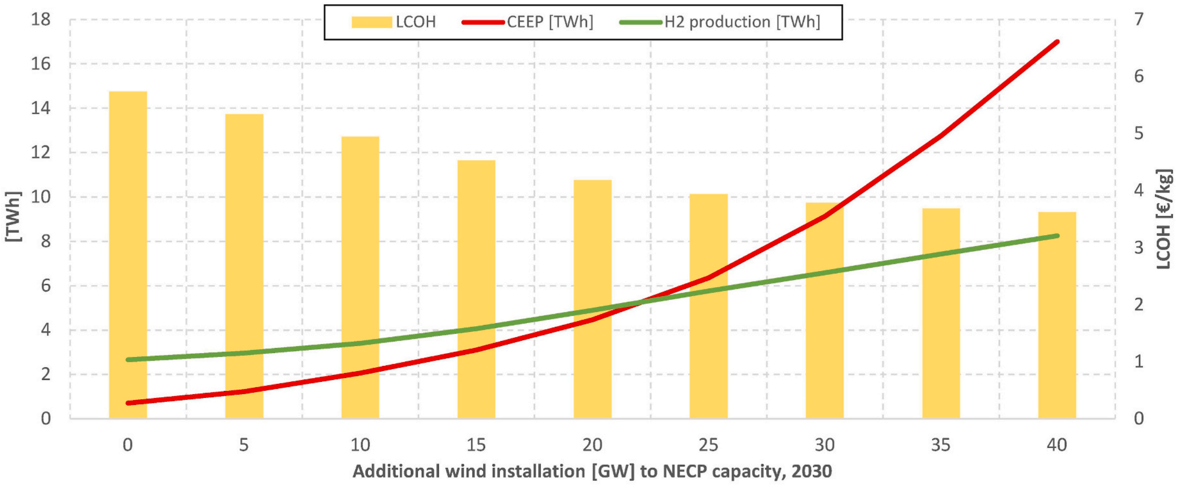

Fig. 10. LCOH, CEEP, H_2 production as wind capacity increases.

achievement, can't be weighted just on a single parameter. Therefore, three regions of feasible solutions have been set, in order to better detect the not dominated Pareto solutions, by exploiting the corresponding Pareto front. In this analysis the multi-objective problem has been performed by considering the Equation (8). The iterated parameters are represented by the PV and wind additional installation capacities. Those values have been analysed in step of five GW in a bounded range by 0 and 40 additional GW per source. As explained in the methodology and depicted in Figs. 11–13, the optimal scenarios identification is based on a trade-off of yearly hydrogen production, critical energy excess production, LCOH values and total investment costs. All figures represent the different placements of the simulated PV-wind installation scenarios, based on the optimization parameter. In accordance with the axis, the Pareto front is easily identifiable in each region of feasible solutions. The different colour tones depict the additional installation costs, as shown in each label. In Fig. 11 the installation scenarios, arranged according to the minimisation of LCOH and additional installation costs, together with the yearly hydrogen production maximisation are depicted.

From the LCOH minimisation point of view, the best scenarios should encompass higher hydrogen production, as foreseen in Equation (1). That approach would entail considerable RES installations and, consequently, significant additional costs. Indeed, for achieving a competitive LCOH value, close to 3.5 $€/kg_{H2}$, more than 40 billion € of additional investment costs are needed. The LCOH minimisation would also lead to elevated CEEP values, as shown in Fig. 12, implying significant drawbacks. The LCOH lessening can be achieved by reducing CEEP and hence by decreasing the LCOE as well. The same effect can be attained by increasing the hydrogen production and consequently increasing the PV/wind installations. In such a way the Pareto front provides various installation scenarios. The lasts are characterised by different additional installation costs. On the other hand, Fig. 13 indicates that the CEEP reduction entails an excessively low hydrogen generation.

Substantially, the PV and wind installation scenarios maximising the hydrogen production and minimising the CEEP and LCOH values require high additional investment costs.

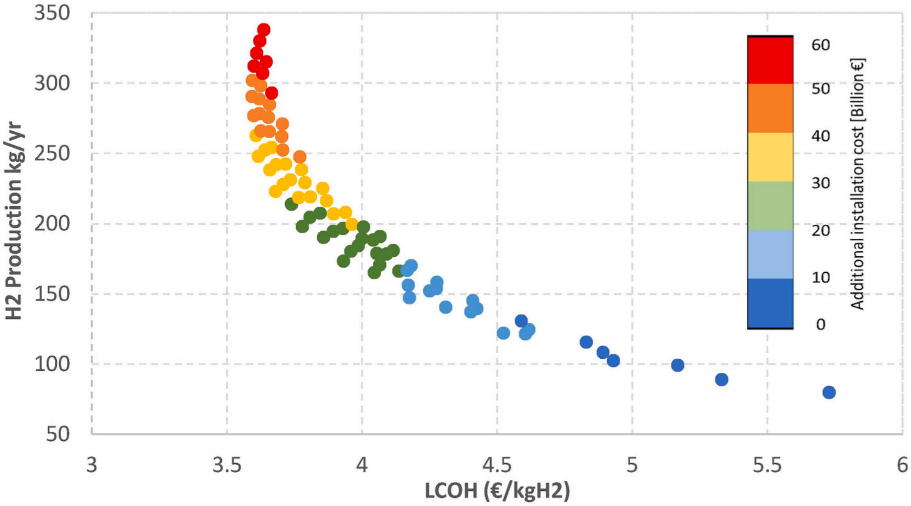

Fig. 11. Region of feasible solutions, LCOH-H_2 Pareto front.

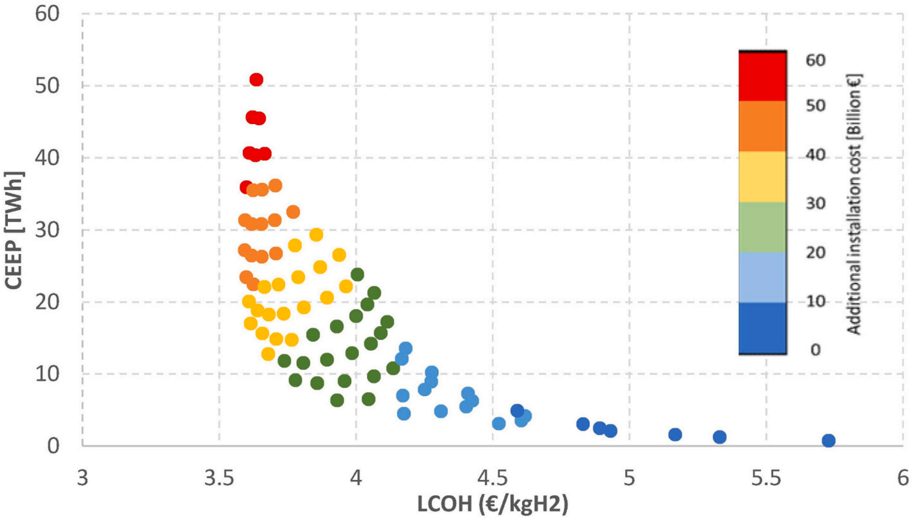

Fig. 12. Region of feasible solutions, LCOH-CEEP Pareto front.

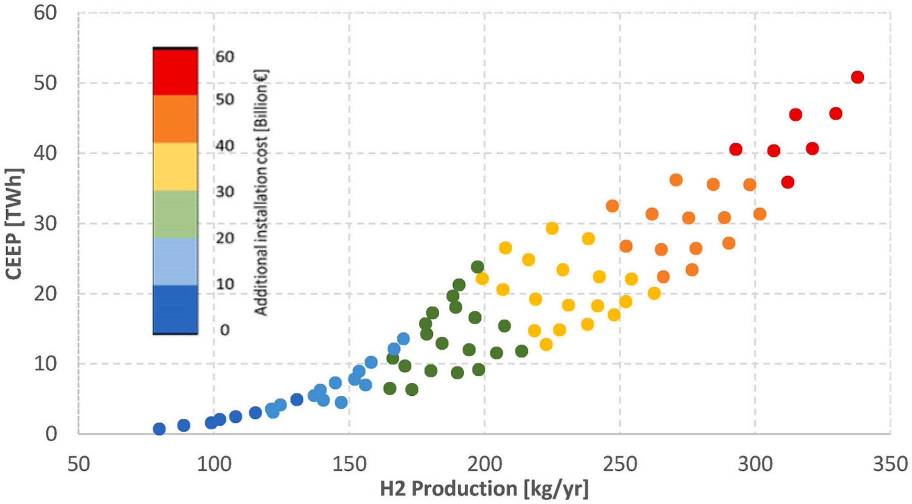

Fig. 13. Region of feasible solutions, CEEP-H_2 Pareto front.

As it is emphasized in Fig. 12, since the LCOH minimisation implies the CEEP increase, more interconnection strategies [23,64], such as power-to-heat [65] and power to vehicle, are appropriate for meeting and exploiting the CEEP generation [66].

The optimal scenario identification has been computed by the means of the Utopia Point detection. The five optimal PV and wind additional installation scenarios are shown in Table 4.

Summing up, the total suitable additional RES capacity amounts to approximately 30–35 GW, split between PV and mostly wind technologies.

3.5. Sensitivity analysis

In order to determine the robustness of the LCOH analysis in the 2030 Italian best scenarios, a sensitivity analysis has been performed to evaluate the potential LCOH variation as a function of the electrolysers' CAPEX. This latter value has been considered equal to 450 €/kW, as benchmark in 2030. Nonetheless, the technological challenge foresees a significant electrolysers' installation cost reduction. That opens a new development in the hydrogen economy allowing the electrolysers quality leap, by moving from niche technologies to mainstream technologies. The goals for the challenge involve installation cost decrease to a value even smaller than 200 $/kW, longer lifetimes up to 50 thousand full load hours and higher efficiency up to 80% as well [58]. The achievement of those targets seeks an economy of scale and technological innovations. However, as the improvement of one aspect often adversely affects another parameter, some trade-offs between the targets is the key for the most suitable technologies. In Fig. 14 new LCOH values, coming out from the CAPEX variation in the optimal detected scenarios, have been depicted. The sensitivity analysis has been performed by using a range of installation costs bounded by 250 and 650 €/kW.

Fig. 14 points out that as the electrolysers' CAPEX amounts to 250 €/kW, the LCOH values of the "0 PV -30 WIND" GW and "5 PV -30 WIND" GW scenarios almost overlap. In such a case the additional investment, caused by further 5 GW installation of PV plants, it is not convenient for the LCOH minimisation.

Owing to the electrolysers' cost reduction, the LCOH value falls down the 12/13% per each scenario, by considering a variation CAPEX from 450 to 250 €/kW. In Fig. 15 the LCOH lessening is emphasized, by the comparison between the scenario depicted by the NECP and the detected optimal scenario as well.

The main aspect that preponderantly emerges from Fig. 15 is the lower weight of the electrolysers' installation and O&M cost in the LCOH assessment. The cost associated to the technology influences the outcomes to be almost halved in the optimal scenario. Therefore, the most significant impact in the LCOH computation is held by the renewable energy cost. This latter accounts over the 72% and 82% of the LCOH evaluation in the case of electrolysers' CAPEX of 450 and 250 €/kW in the optimal scenario, respectively.

3.6. Limitations of the present work

It should be pointed out that in the present work only the hydrogen blending into existing natural gas pipelines has been considered as energy end-use option. Different pathways have not been investigated, since this paper focuses on the power-to-gas value chain for green hydrogen production as a means of balancing system.

Further research is recommended by evaluating and integrating the foreseen H_2 demand to the designed 2030 Italian energy system to enrich and complete the final hydrogen supply chain echelon. Such purposed evaluation allows to assess the interaction between the components of the hydrogen supply chain and the uncertainty of the green hydrogen demand. Thus, the comparison of distributed and centralized hydrogen generation in each energy scenario can also be addressed.

Finally, a limitation of the present work regards the 5 GW step of supplementary RES installation for performing simulations. New and more accurate additional PV and wind settings can be computed in connection with higher simulation numbers. Such issue can be overcome by coupling the proposed methodology with genetic algorithms and it can be considered a further development of the present work.

4. Conclusion

In this study a makeover of the Italian 2030 RES installation goals has been performed, building on the targets envisaged by the National Energy and Climate Plan's document. The presented results have been carried out in order to fulfil the Hydrogen Italian Roadmaps goals, that encompass the 5 GW of electrolysers' capacity by 2030 and the market uptake of the hydrogen in the Italian energy demand up to 2%. This last value amounts to 0.7 million tons of hydrogen production.

The simulation of the Italian energy system has been performed by means of the EnergyPLAN software, that enables the hourly analysis of the energy flows. In so doing, it has been possible to estimate the renewable energy overgeneration exploitable by the electrolysers and the critical excess of energy production not embeddable in the Italian energy system. Thereafter, the outputs supplied by the software have been complemented by a breakdown model for identifying the overgeneration renewable source share. Thereby, an economic analysis of the involved technologies has been carried out for each different RES setting. New PV and wind installation scenarios have been detected. Those latter, in the face of the foreseen 2030 Italian energy demand, provide more competitive levelized cost of renewable energy and consequentially lower LCOH production than the computed values of the NECP's capacity targets. The detected optimal scenarios envisage a significant growth of wind capacity, up to additional 35 GW. Even though the photovoltaic further addition is related to higher LCOH values, it results a suitable renewable technology for accomplishing the new decarbonization targets. The optimal scenario foresees an aggregate capacity that amounts to 52 GW and 54.3 GW of PV and wind installation, respectively.

In conclusion, the main outcomes of this work can be summarized as follows:

- The minimum LCOH values achieved amounts approximately to 3.6 €/kg.
- 35 GW of RES' installation are needed in addition to the 52 GW and 19.3 GW PV and wind installation goals, envisaged in the NECP, in order to achieve the Italian Hydrogen Strategy's objectives.

Table 4
Best RES scenario detected.

Value	$P_{solution}$ [/]	LCOH [€/kg]	H2 production [Million kg]	CEEP [TWh]	Investment [Billion €]	Additional PV/wind capacity [GW]
U P	/	3.59	337.96	0.7	0	/
#1	0.723	3.68	222.88	12.76	30.80	+0/35
#2	0.725	3.78	197.91	9.13	26.40	+0/30
#3	0.73	3.74	213.84	11.81	29.48	+5/30
#4	0.738	3.86	190.10	8.73	25.08	+5/25
#5	0.739	3.81	204.50	11.52	28.16	+10/25

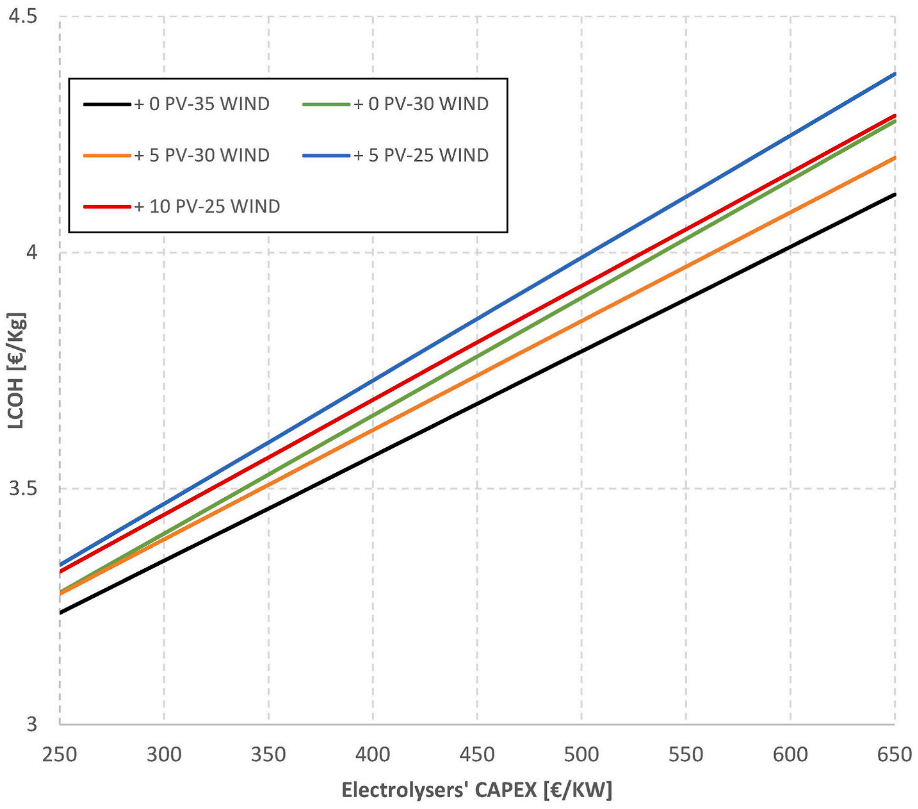

Fig. 14. Sensitivity analysis.

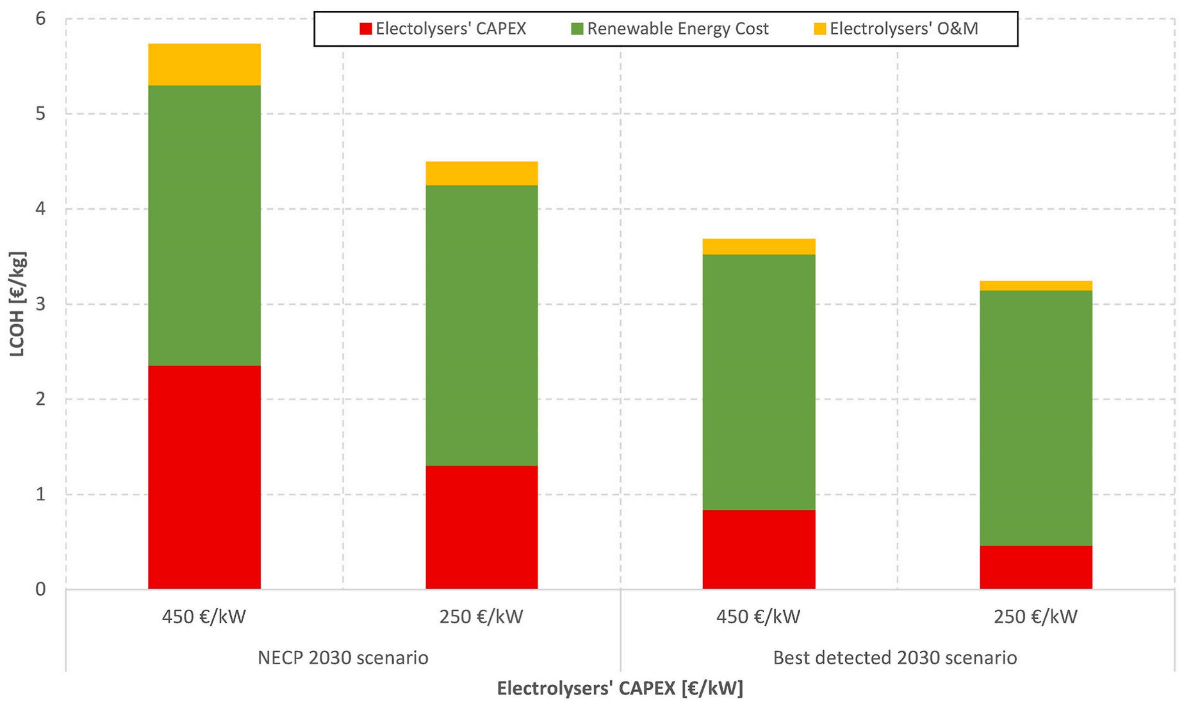

Fig. 15. LCOH breakdown in cost.

- Wind energy is the most suitable source to address the economic competitiveness related to the Italian hydrogen production cost.
- The additional RES capacity is correlated to lower levelized cost of renewable energy exploitable for the electrolysis process. The 2030 LCOE values recorded in the NECP simulated setting and in the most suitable scenario amount to 61.03 €/MWh and 55.59 €/MWh, respectively. New feed in tariff and less red taps can represent the key for achieving a new development in the hydrogen economy.
- Additional PV installation leads to higher CEEP value than wind installation increase. As a result, the lowest LCOE has been recorded

in the scenario that includes 0 and 30 additional GW of PV and wind technology, respectively.
- The LCOE parameter is the most relevant in the LCOH assessment. In the best installation scenario, the LCOE weights the 72% of the LCOH. In case the electrolysers CAPEX would reduce up to 250 €/kW, the LCOE would impact the 82% on the LCOH value.
- The RES installation increase is correlated to higher electrolysers' full load hours and consequently increasing green hydrogen production. In the best scenario 2151 h per year have been foreseen and a total yearly production of 222.88 million kg of hydrogen has been estimated. Those values result increased almost tripled compared to electrolysers' full load hours and hydrogen production calculated in the NECP scenario.

To implement the current methodology 25–30 billion € are needed in addition to the cost foreseen in the NECP.

- The critical excess of renewable energy production, owed to the LCOH minimisation and higher RES installation values, amounts to 12.76 TWh in the best 2030 installation scenario. It cannot necessary be considered as a drawback, since it could be exploited by means of other energy storage systems or sector coupling strategies, such as power-to-heat or power to vehicle systems.
- Significant hydrogen production increase occurs at greater wind additional capacity. In detail, an additional 40 GW wind installation leads to electrolysers' full load hours up to over 4 times the achievable ones matching the NECP installation targets.

The method proposed in the present work turns out to be a viable approach for assessing the optimal additional RES installation targets necessary for accomplishing the deployment of the hydrogen value-chain. Such a work proves how case-sensitive the planning stage results and that a multi-decisional approach plays a key-role for it. In detail, the results of the present work show how the hydrogen energy planning process must be carried out not as a single issue but evaluating the hydrogen role in the whole energy system.

The proposed approach takes into account four dimensions for the optimization process, nevertheless, other aspects can be easily included.

Moreover, the methodological approach can be replied in different case studies since it exploits a well-established software in literature as one of the most important and widely used tools for the energy planning. A similar analysis can be performed relying on the current approach for different scales of application, as for instance hydrogen valleys, and for other time horizons as well.

Furthermore, the outcomes of the present work can give insights for policymakers about the complexity of the hydrogen energy planning process, the required additional RES capacity for the hydrogen value-chain development and the different aspects affected by both the RES deployment and the electrolysers installation.

CRediT author statement

Antonio Sgaramella: Formal analysis, Software, Writing - original draft. Lorenzo Mario Pastore: Conceptualization, Writing - review & editing. Gianluigi Lo Basso: Supervision, Writing - review & editing. Livio de Santoli: Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Nomenclature

CAPEX	Capital expenditure
CEEP	Critical excess energy production
$CO_{2,eq}$	CO_2 equivalent
crf	Capital recovery factor
ELT	Electrolyser
EU	European Union
FLH	Full load hours
GHG	Greenhouse gases
H_2	Hydrogen
LCOE	Levelized cost of energy
LCOH	Levelized cost of hydrogen
LHV	Lower heating value
NECP	National energy and climate plans
NG	Natural gas
O&M	Operation and maintenance
OPEX	Operation and maintenance costs
PtG	Power-to-Gas
PV	Photovoltaic
R&D	Research and development
RES	Renewable energy sources

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