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The role of hydrogen from electrolysis in the overproduction of energy fromrenewable sources

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Abstract. The annual production from renewable electricity sources in Italy has been considerably growing and in some areas, in particular Southern Italy, there is constantly an overproduction of electricity during the peak hours of insulation due to the photovoltaic systems. Such excess electric energy could be used to produce large amount of hydrogen by electrolysis, thus covering approximately 3.3% of the yearly national industrial hydrogen demand and avoiding emissions of approximately 85,000 tons of carbon dioxide.This work shows that few large alkaline electrolysis plants, located in strategic sites and supplied with this excess energy, can just now produce hydrogen for industrial use at competitive costs. Furthermore, the presence of electrolysis plants connected to the main electricity grid would represent a controllable element useful for its regulation and stability.

1. The renewable energy production in Italy

For over a decade, Italy has been witnessing a continuous growth in the installation of energy production plants from renewable sources. In figure 1, which shows the variation in gross installed power over the last eighty years by type of plant, we noticed (a) a general increase in the overall value, due to a progressive increase in consumption and the industrialization of the country and (b) the substantial increase, in the last twenty years, in the share of renewable energy plants, in particular wind and photovoltaic, to the detriment of energy produced from fossil sources.

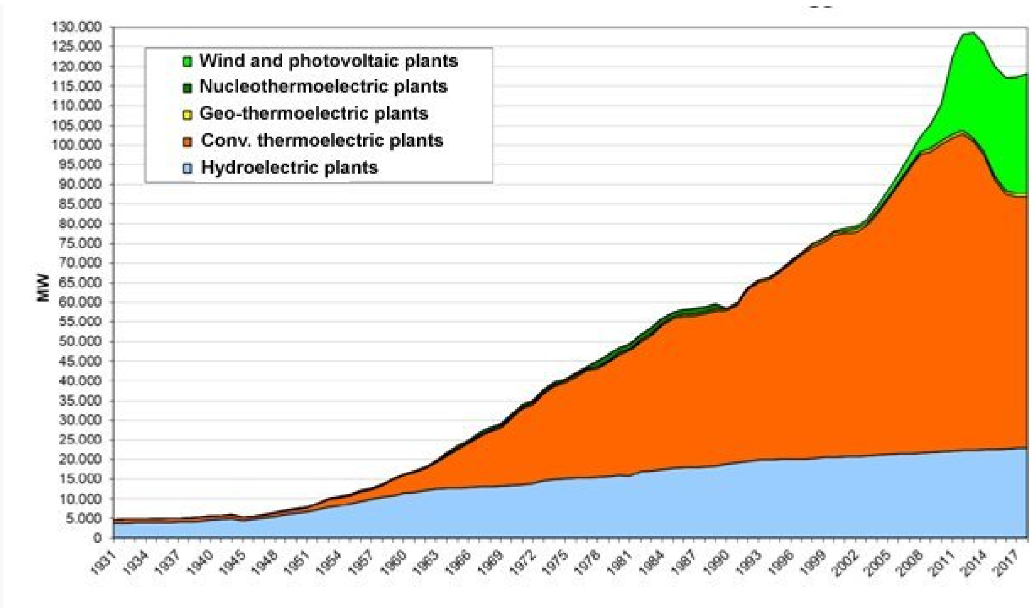

Figure 1. Gross efficient power installed in Italy from 1931 to today [1].

Figure 2 details how the overall national energy demand is distributed among the various type of primary resource. Energy consumption in Italy has been diversified considerably in the last decade, depending less on oil againsta considerable growth of the energy production from renewable energy sectors:in 2019 against an installed power of 119.3 GW and an overall energy consumption of 294 TWh, the contribution from renewable energy was approximately 114.4 TWh, equal to 38.9%. A substantial part of thisenergy is related to the so-called renewable electricity (wind and photovoltaic, ER_{el}) which, with their 42 TWh of consumption, corresponds to about 14.2% of the total energy national production.

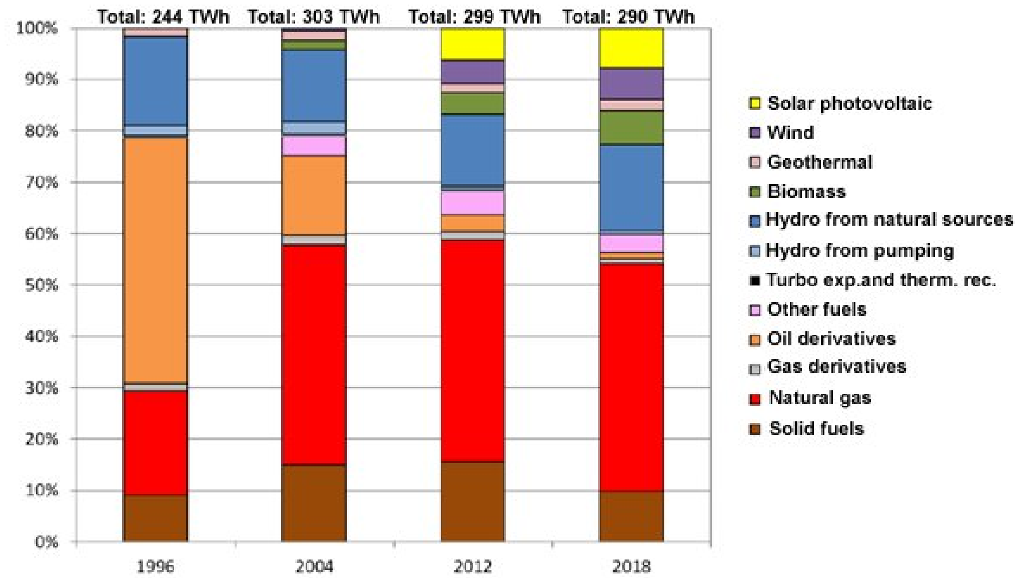

Figure 2. Variation of the energy production mix [1].

In order to achieve the 2030 objectives indicated by the Integrated National Energy and Climate Plan (PNIEC) [2], an increase of about 39 GW in ER_{el} sources will be added at the current installed one (31.6 GW - 2019), so reaching a total of 70.5 GW (2030), a value of ER_{el} power more than double of the present one.

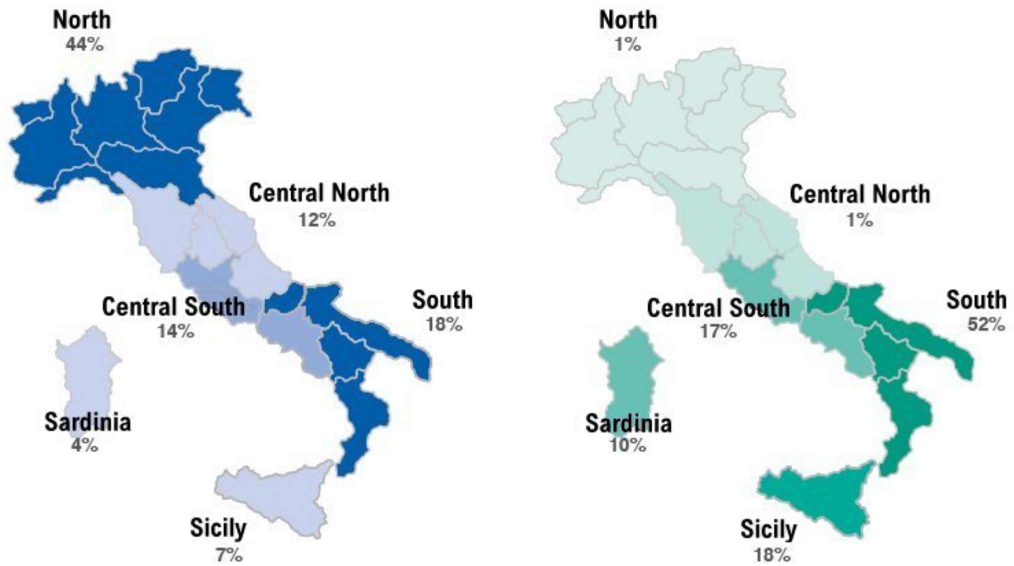

Figure 3. Photovoltaic (blue) and wind (green) power installed in Italy by market area in 2018 [3].

In Italy energy production from wind and photovoltaic power plants is not always homogeneously distributed (figure 3): if the energy produced by photovoltaics in the North (10.2 TWh) is quite similar to that produced in the South (10.1 TWh) (but with different installed power), the share of wind energy produced in the North is instead significantly lower (0.26 GWh vs 18.1 TWh) [3].

This imbalance in the production of energy from renewable sources, typical of other European countries, would not have great consequences if this energy were consumed and managed in the respective production areas. In Italy, even if globally the production of energy from renewable electricity is generally always lower than the daily demand for electricity (figure 4), in specific areas this can't be true. So while in the North the daily demand for electricity can absorbregularlyall production from renewable, in the South, in the same average day and in the few central daytime hours, this production of energy can exceeds the electricity load demand (figure 4).

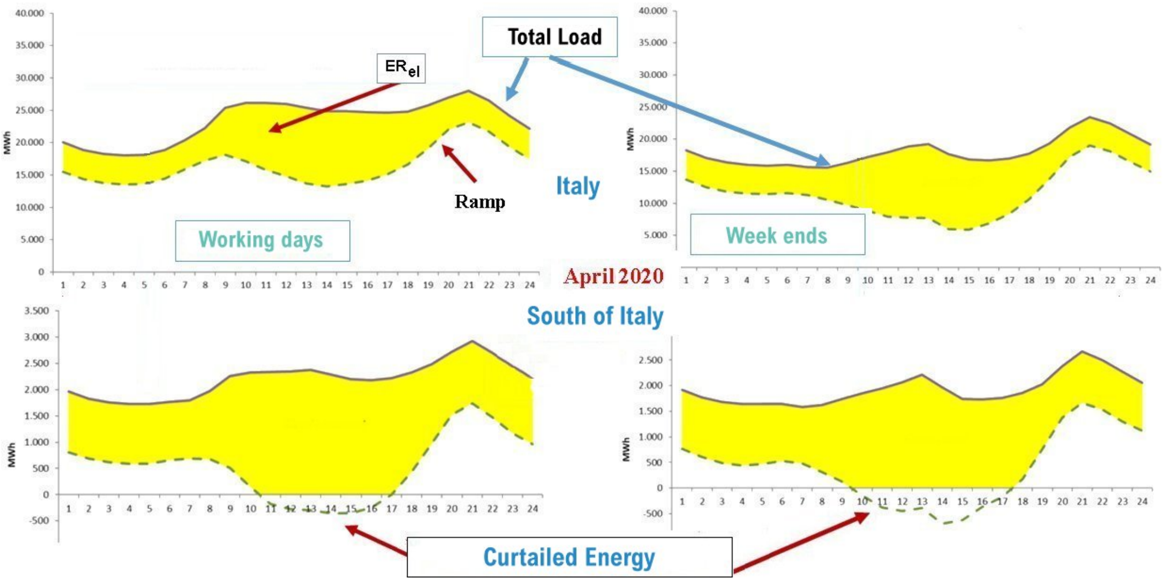

Figure 4. Daily average profiles of energy consumption in Italy and the South in working days and weekends [1].

The local energy overproduction from renewable energy (due mainly to PV plants in the peak insulation hours) forces the national electric grid operator to act, transferring as much as possible this excess energy on the distribution and transmission network and, eventually, by disconnecting part of the renewable generation plants (generally Wind energy). This amount of electricity not absorbed annually by the grid (MPE: Mancata Produzione Eolica – *in italian* - Wind Production Lack) exhibits a growing trend (fig. 5), and looks to be greater with the expected increase in share of renewable electricity. Furthermore the electricity grid operator generally has to pay the producer a fee, currently very low (0.04 Euro/MWh in 2018) [4], to compensate for the lack of production and consequent sale of wind energy.

Figure 5. Evolution of relative energy to the MPE divided by commercial regime [5].

2. Overproduction of energy and demand for hydrogen

Considering this regional energy overproduction and with the aim of evaluating a possible solution for its profitable use, we hypothesize to produce hydrogen from electrolysis using this excess energy (figure 6).

The concept, certainly not a novelty in the integration studies of small or medium electrolysis plants in combination with renewable energy, consists in diverting this excess energy present in the electricity grid to electrolysis plants for the production of hydrogen [6].
Over the past decades a considerable number of this type of plant has been studied and demonstrate, in different sizes and with various technologies and control logics, then demonstrating their technical feasibility but also the strong dependence of the economy of these plants on the availability of low-cost electricity [7]. One of the driving reasons behind the hypothesis presented here is just the availability of a surplus energy and the possibility of conceiving the electrolysis system itself as a controllable element of the national electrical network, capable to absorb it and at the same time useful for by battery systems [8] and abroad on electric grid for frequency control [9], support this hypothesis. its regulation and stability. Similar exploratory experiences, conducted in Italy on electric grid.

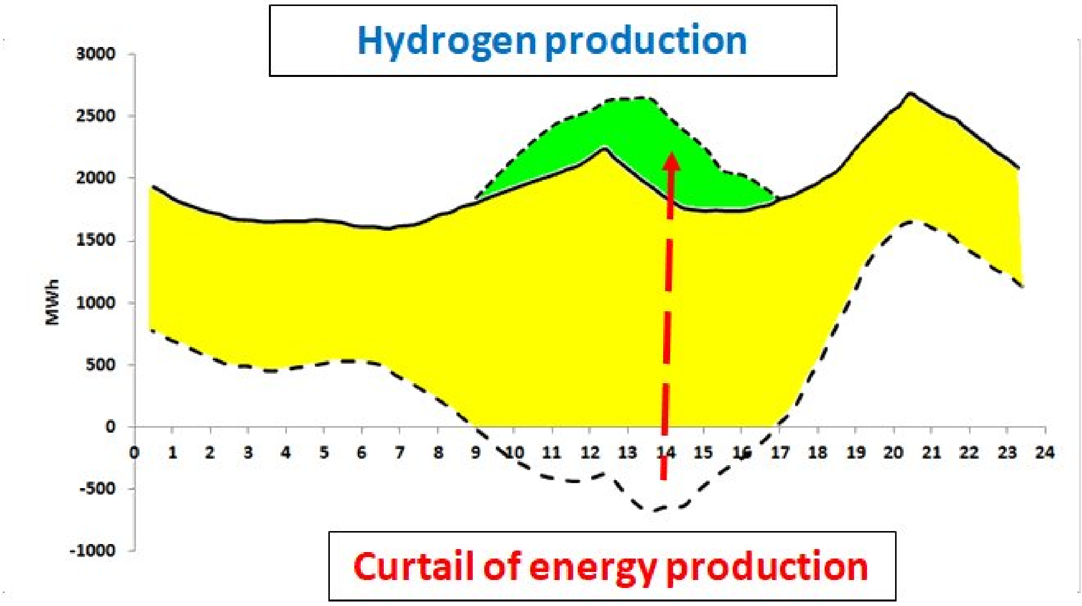

Figure 6. Excess daily renewable energy profile can be used to produce hydrogen.

To have a rough estimate of hydrogen production with the current excess energy of the network, and its impact on industrial consumption in Italy, an electrolysis efficiency of 65% was considered in line with the current values indicated by this type of plant.
According to official electric grid data [5], the lack of energy injected by renewable electricity plants (mostly Wind energy) amounts to approximately 815 GWh in 2020, whose distribution in the southern regions and islands is shown in table 1, estimating it divided according to the share of renewable electricity supplied by each.

Table 1. Distribution of energy consumption in Southern Italy from renewable electricity sources [10].

	Wind/GWh	PV/GWh	ER_{el}/GWh	Regional prod/%	Total GWh/year
Molise	662	231.2	893.2	3.2	25.7
Abruzzi	410,2	945.5	1355.7	4.8	39.0
Calabria	2132.4	681.3	2813.7	9.9	81.0
Sardinia	1677.1	1154.7	2831.8	10.0	81.5
Basilicata	2423	491.3	2914.3	10.3	83.9
Campania	3209.2	981.5	4190.7	14.8	120.6
Sicily	2765.4	1911.3	4676.7	16.5	134.6
Apulia	4801.9	3839.2	8641.1	30.5	248.7
TOTAL	18081.2	10236.0	28317.2	100.0	**815.0**

With the current excess energy from the national electric grid approximately 16,000 tons/y of hydrogen could be produced, equivalent to 3.3% of the hydrogen consumption in industry, that amounts to about 480,000 tons/y (16 TWh/y - LHV 120 MJ/Kg) [11].
With the amount of excess energy from renewable sources produced in the various regions, and assuming an average daily operating time of 6.5 hours/day, it is possible to obtain the total power of electrolysers required for each region to absorb such a surplus of energy (figure 7 left). These hypothesized values have only an indicative value, and their main purpose is to show the order of magnitude of the required electrolysis units. A 10 MW electrolysis plant was used as a standard unit as already operating in other countries [12,13,14], and as it can provide a roughly estimate of the number of electrolysis units per region (figure 7 right).

On the basis of the increase in power of the ER_{el} plants foreseen in 2030 by the PNIEC (70.5 GW) and assuming conservatively that the excess energy maintains the same percentage of current proportions with respect to consumption (1.95%), it is possible to calculate the future yearly excess (1,817 GWh) and therefore, estimate the production of hydrogen at that date which would be around 35,000 tons/y, equivalent to 7.7% of the current consumption of hydrogen, still a limited fraction of the total consumption. This forecast estimate assumes that electricity consumption remains unchanged.

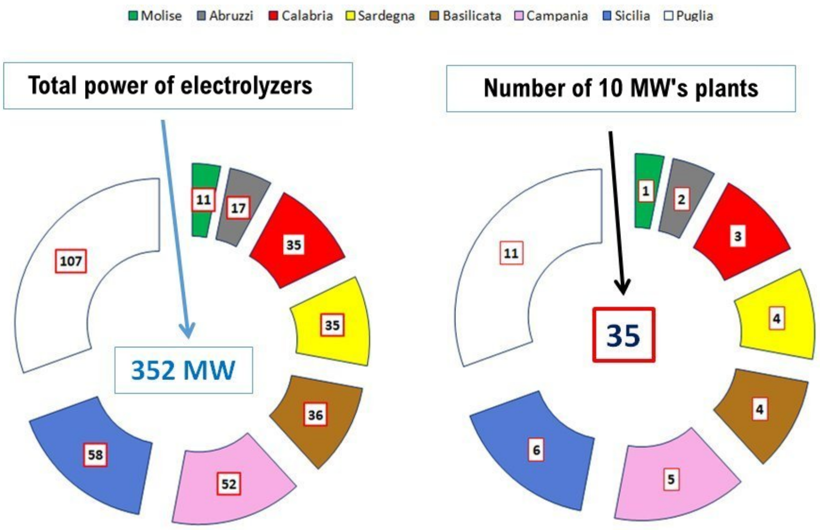

Figure 7. Estimation of the regional amount and distribution of standard 10 MW electrolysis units to be installed to absorb present local excess ER_{el}.

The current hydrogen market is aimed at four main sectors: chemistry, refining, metal working and diversified industrial applications [15]. The largest quantity is consumed for over 90% in the first two sectors, while the remainder (about 48,000 tons/y) is produced in specific plants and supplied in cylinders, tankers, as gas and liquid, to various industrial sectors (e.g. steel mills, food industry, semiconductors, glass, etc.). These latter sectors could be the first recipients of electrolytically produced hydrogen in terms of quality, quantity and distribution methods.

Presently, the hydrogen market is diversified, and hydrogen producers are often self-consumers, as they produce large quantities of hydrogen exclusively for their own internal industrial consumption (ammonia, methanol, resins). There are also manufacturers on behalf of third parties, able to resell variable quantities of hydrogen produced in dedicated plants, and sometimes these plants are part of the same industrial areas or are connected to specific industries. Finally, there are also industrial sectors that produce hydrogen as a by-product of other processes (e.g. chlorine production plants). The boundary between these subjects is not always defined (figure 8): self-producers (1) can become suppliers of the retailers themselves in case of overproduction (2) or consumers in case of need (3) as well as producers from other processes they can become suppliers of the former (5-7) or of the latter (5-6).

The location of the plants in Italy (figure 9) shows a distribution over the entire national territory with a certain concentration in the industrial areas of the North-West of the country but also in the South, in particular Puglia and Sicily.

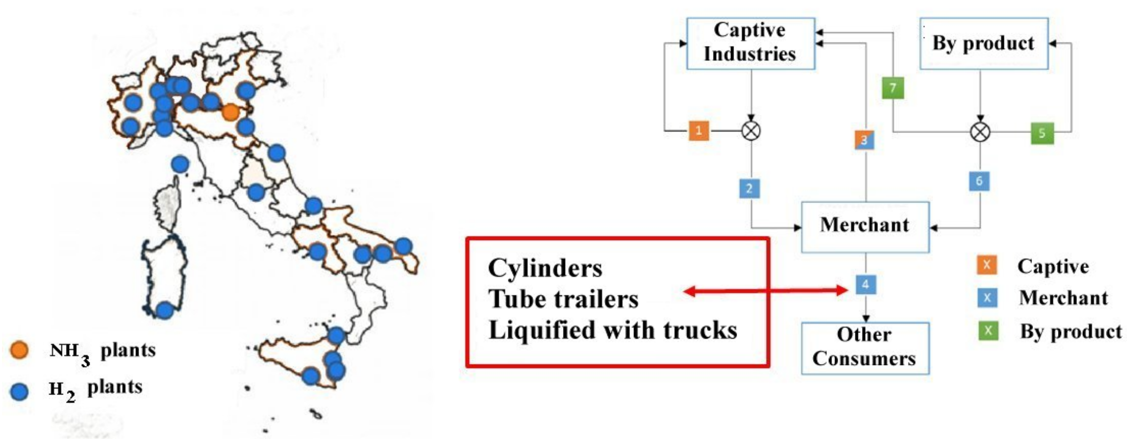

Figure 8. Definition of types of hydrogen production based on availability [15].

Once the order of magnitude of the various regional plants necessary to absorb the surplus energy has been established, the next step could consist in identifying their location. Here it is necessary to introduce considerations that take into account various factors that are with priority in charge of the national electric and gas grid operators (figure 9), whose main objectives are to ensure the stability and the quality of the respective service.

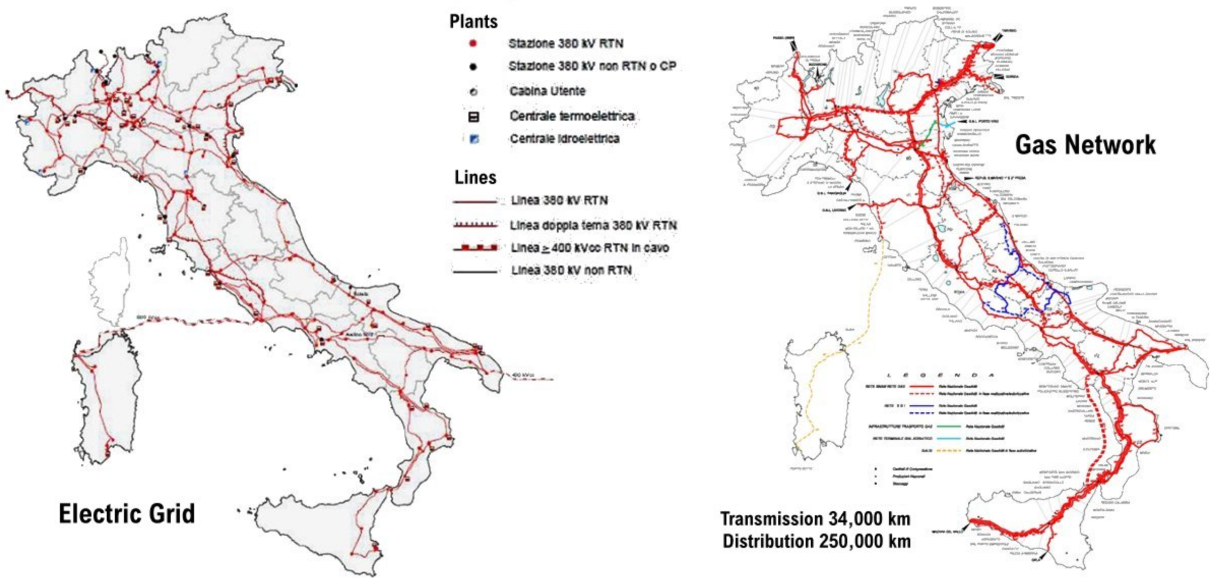

Figure 9. Configuration of the electricity network (left) and gas line network (right) in Italy.

A series of criteria can be indicated to identify potential sites:

- congestion points of the Medium Voltage electricity network
- presence of industrial activities for a direct use of pure hydrogen
- proximity to the gas network for possible injection (P2G - Power to Gas)

The large, fast and almost continuous adjustable load of an electrolysis system could represented an effective and rapid element to be placed in critical sites along the electrical network for the electric energy balance.

It is clear that a large number of sites, while allowing better distributed network control, would have higher investment and management costs. A concentration of several electrolysis modules in few sites would benefit of economy of scale, due to less critical auxiliary systems (inverters, rectifiers, water and gas purification systems, compressors, control systems, battery, etc.) and for a greater flexibility in optimal management of the system and maintenance of the individual units.
Industrial end users in the vicinity of the plant itself would be favorable, so as to minimize storage, compression and transport systems; the direct and immediate use of the high purity hydrogen (oxygen as well) produced would be ideal.
The presence of the gas network for a possible injection into the network, even if it does not appear to be the optimal solution from a chemical and thermodynamic point of view, could be still an enough simple and economical solution to implement in the future, once the concentration constraints and piping materials issues have been overcome.
These large electrolytic hydrogen production plants directly connected to the electric grid could be substantially standardized and modular, easily expandable according to the requests for increased power and needs of use. Compared to the various demonstration electrolysis plants connected with wind or photovoltaic systems and built up to now, the specifications of such an industrial electrolysis systems look more standardized and economically competitive, having specific and more constant electrical characteristics as input energy data and consequently optimized and standardized electrical, power electronic, electrochemical and auxiliaries components (stack, deoxo, reverse osmosis, compression, AC/DC and DC / DC converter, sensors, etc.).

3. Comparing technologies: alkaline and polymer electrolysers

The low-temperature electrolysis technologies currently mature to meet the needs highlighted above in relation to the quantities of hydrogen to be produced and the power required are essentially two: alkaline electrolysers and polymeric membrane electrolysers (PEM: Polymer Electrolyte Membrane). Alkaline, commercially more widespread, are generally larger in size and have lower costs due to the absence of precious metals group electrocatalysts (PGM: Platinum Group Metal). Table 2 compares the technical characteristics of two electrolysis stacks of similar power (AC-485 alkaline and polymeric PEM-MC-400), both manufactured by NEL (Norway), an industry with almost a century of experience in electrolysis technologies.
The choice of similar units in production capacity (413 for alkaline and 485 Nm^3/h for polymeric one) makes the technical characteristics and performances comparable. By coupling multiple stacks, larger plants can be created, e.g. the alkaline A3380 (2.1 MW) consisting of 8 AC-485 modules and the polymeric M4000 (1.8 MW) composed of 10 MC-400 modules.

Table 2. Comparison table of alkaline and polymer electrolyser [16].

Parameters	**NEL AC485**	**NEL PEM-MC400**
Net production rate	485 Nm^3/h	413 Nm^3/h
Prod Capacity dynamic range	15%...100% of flow range	10%...100% of flow range
Delivery pressure	1-30 bar (g) 200 bar with additional compression	1-30 bar (g) 200 bar with additional compression
Spec. power consumption	4.40 kWh/Nm^3	4.53 kWh/Nm^3
System electrical efficiency	67.7 %	65.7 %
Hydrogen purity	99.6 % (99.99 with purifier)	99.9998 %
Electrolyte	25% KOH solution	PEM
Feed water consumption	0.9 l/Nm^3	0.9 l/Nm^3 (H_2O a 0.1 μS cm^{-1})
Footprint	225 m^2	160 m^2
Stack life time	> 10 years	Not verified
Catalyst – Material	No PMG	PMG (Ir,Pt) – Ti, Nafion©

The modularity of the electrolysis systems for both technologies with a stack size limit simplifies a series of problems such as pressure seal, fluid dynamics (two-phase electrolyte gas mixture), maintenance and the electrical supply to the entire plant.
The ability to operate at partial load, a condition that should be typical when the electrolysis plant is powered by renewable energy, is broad for both technologies, more limited for the alkaline electrolyser given the greater diffusion of gases through the membrane with the consequent risk of formation of explosive mixtures, especially in the stand-by phases. It should in any case be considered that, with the presence of multiple electrolysers modules and with careful management of the energy entering the production site, the limit operating conditions could be kept under control.
A similar argument can be applied to the production of hydrogen under pressure, where an initial level of pressurization could be implemented directly inside the electrolyser itself, thus reducing the subsequent compression stages. Although potentially more adapt for high pressure operation, the long-term performance of the polymer electrolyser still needs to be verified in the field in high power units, when periodic and repetitive stack pressurization could produce pernicious relaxations in the sealing parts. At the moment a compression system downstream of the electrolysers, with adjustable pressure levels, adapted to the requested service of hydrogen, looks to be the most practicable, albeit probably less economical solution.
Both technologies have no differences in the electrical power supply system as well as in the auxiliaries required for the treatment of the gas produced (elimination of impurities and drying), with less work required for the PEM technology given the better quality of the gas at the outlet. Not so for the process water supply, where the very low conductivity levels required by PEM technology (~ 0.1 μS cm^{-1}), to avoid membrane contamination, lead to the adoption of additional purification

technologies (osmosis systems). The membrane contamination requires a continuous control of the conductivity of the circulating electrolyte and its constant purification, in order to eliminate the traces of ions released by the materials making up the circuit. Membrane contamination poses a great risk to the reliability and performance over time of polymer electrolysers. The footprint of the plant favors PEM technology, with more compact and smaller electrolysers, although, being industrial plants, this aspect appears to be of lesser importance.
Regarding the quality of the circuit materials and catalysts, if for the alkaline electrolysers the aggressiveness of the electrolyte (sodium and potassium hydroxide) leads to the use of adequate components in the circuitry, in the polymeric ones it is the stack section (electrodes, membrane and plates) that requires valuable and very high-quality and expensive materials (Pt, Ir, Titanium, Nafion®). In particular, the availability and restricted localization of PGMs will certainly limit the extensive use of this technology [17].
From a technical point of view, the alkaline technology appears more adequate and reliable than that of the PEM also by virtue of the fact that these plants have been in operation for many years; as an example, here it is recalled the case of the Norsk-Hydro (now NEL) electrolysis plant, capable of produce 70 ton/day (approx. 150 MW), and operated continuously from 1948 to 1990 (figure 10).

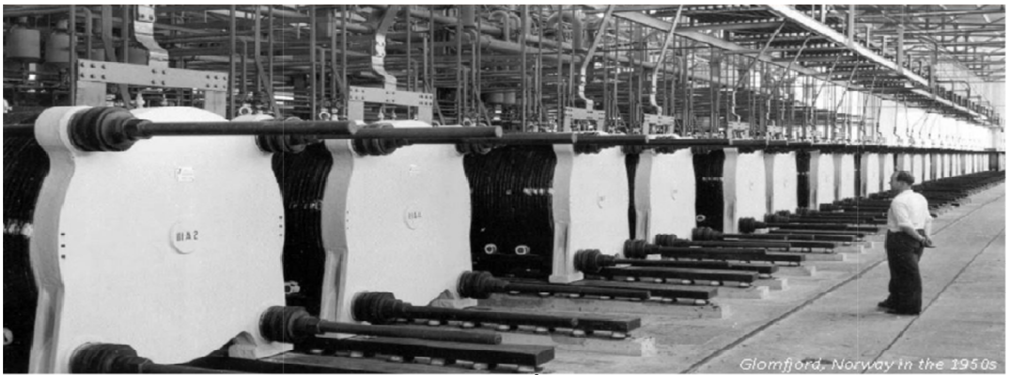

Figure 10. Norsk-Hydro 30,000 Nm^3/h hydrogen electrolysis plant.

4. Economic evaluation of hydrogen production from excess energy

There are many analysis on the cost of producing hydrogen by electrolysis and in general they all show that the cost of electricity as an incisive factor (approx. 60%) [18]. Starting from the specific consumption of the electrolyser (table 2) it is possible to easily construct the theoretical line of the cost of hydrogen as a function of the electricity price alone (0.08 €/kWh industrial price in Italy in 2021) [19], with the slope representing the energy consumption per unit of weight of hydrogen produced. Figure 11 shows the comparison between the lines related to the two models described above (AC-485 with 49.3 kWh/kg of H_2 and PEM M-400 50.7 kWh/kg of H_2) also highlighting the lower theoretical limit of the production cost, assuming an ideal electrolyser (39 kWh/kg @100% efficiency).

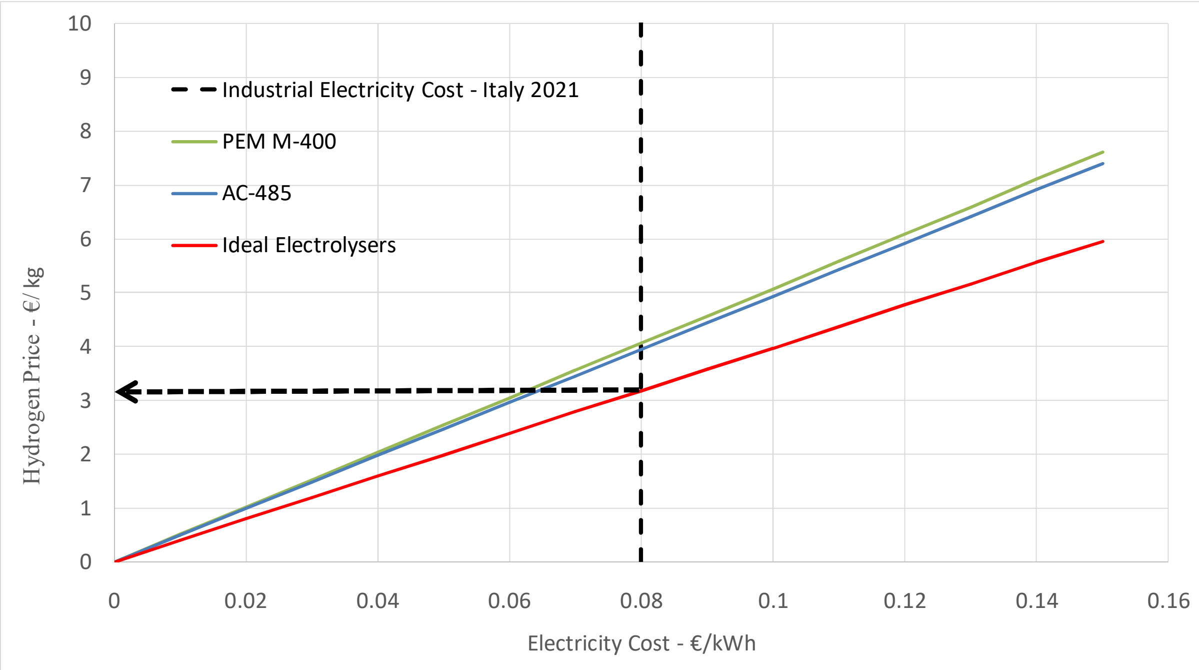

Figure 11. Cost of hydrogen produced by electrolysis (w/o CAPEX) for an ideal system and for the commercial electrolysers of the NEL PEM-M-400 and AC-485.

From figure 11, it can be observed that, with noplant costs (investment, maintenance, disposal, etc.), at the current price of electricity in Italy, the cost of hydrogen cannot fall below 3 €/kg, even using an ideal electrolyser. Obviously, commercial electrolysers have a higher hydrogen production cost (~ 4 €/kg).

A complete analysis, introducing the plant costs, compares alkaline and polymeric electrolysers with the option, for the alkaline one, of using products manufactured in Europe and in China. The additional costs were extracted from the Bloomberg report [20].

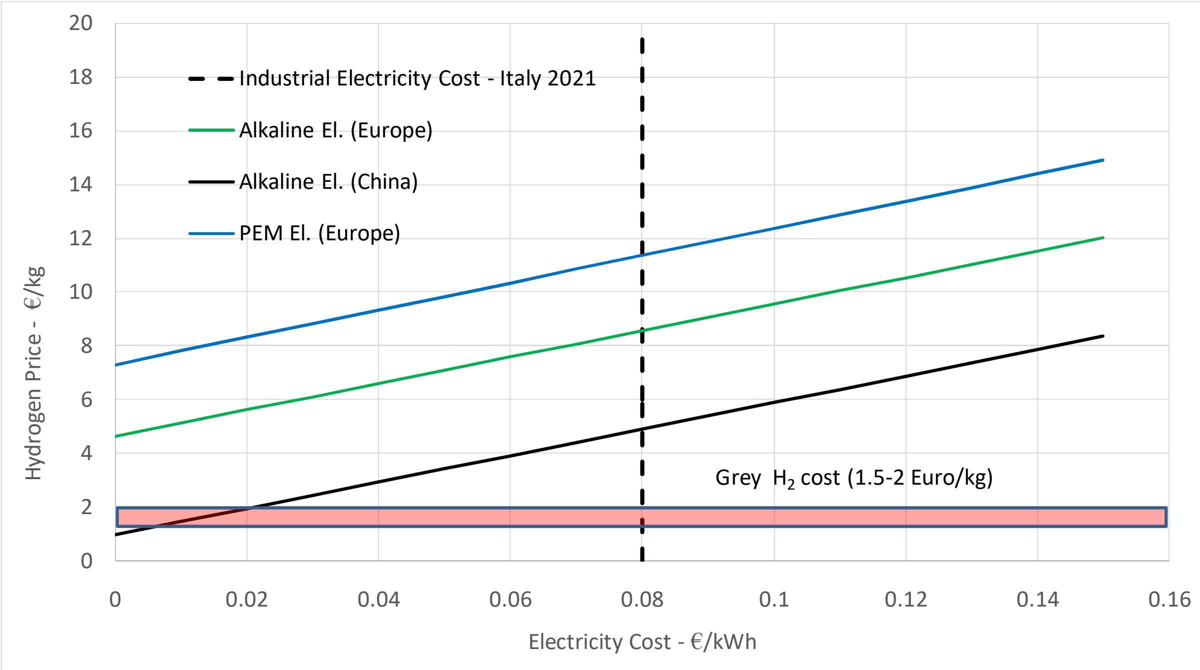

Figure 12. Overall cost of hydrogen produced by electrolysis (CAPEX included) for alkaline and polymeric electrolysers of different production.

In figure 12, with the same efficiencies used previously for alkaline and polymeric products, the straight lines are translated upwards along the ordinate axis by a value corresponding to the so-called "Levelized Cost of hydrogen" (LCOH) or the cost of producing electricity at zero price. At the current price of electricity, the cost of producing hydrogen is between 4 and 12 €/Kg, well above the current market price of hydrogen from fossil fuels (1.5-2 €/Kg) [11]. However, the production of hydrogen from electrolysis could be already convenient in the low cost area of electricity (0-0.02 €/kWh), using Asian alkaline electrolysers.

These values of the cost of electricity could be presently available using the excess energy from renewable energy (0.04 €/MWh in 2018), as shown previously. Producing hydrogen with that energy would be convenient and could be an incentive both for further investments in electric renewable energy and in the electrolytic production of hydrogen itself.

The critical aspect of this result is the cost difference between electrolysers produced in China (about 1/4) compared to those made in Western countries which allows the reduction of production costs [21]. This huge difference is explained by several factors: 1) cheaper raw materials and labor (electrolysers are still largely handmade), 2) higher factory utilization rates: China's electrolyser manufacturing industry is highly concentrated and the top three suppliers together hold a 90% share of the domestic market, 3) demand for their products (in traditional industries requiring on-site small-scale generation of pure hydrogen) stable as linked to the overall growth of the manufacturing industry, which is much stronger in China than in the West. Chinese electrolyser companies have safe and predictable sales volumes and, as a result, their production capacity is well matched to demand, resulting in high utilization rates, particularly for large electrolyser production lines [20].

Although there is a great variability in the LCOH and in its evaluation [22], it is certain that only with large electrical energyfrom renewable energy overproduction the electrolytic hydrogen can be produced at competitive cost with respect to current technologies based on cracking of hydrocarbons.

5. Conclusions

Like any change in technological paradigm, the one proposed by the Italian Ecological Transition will also require an adjustment and/or restructuring of the various industrial realities that are present andactive in these two energy worlds. Historically, the electricity and gas sectors (and in general the electric/power and chemical industries), with their respective national transmission and distribution networks (figure 9), have always proceeded autonomously and independently, with limited technological points of contact. The respective production chains and especially transmission systems have always sought considerable autonomy and a typical top-down approach, due to the complexity of the systems and in order to guarantee the quality of the service offered. The increasing incentives for distributed production from renewable electricity have been already posing big challengesfor how to managethe reverse energy (both electricity and gas) flows (bottom-up), now and more and more in the future. This perspective highlights the need for a structural integration of the two worlds, so as to favor the national energy balance, and the hydrogen production by electrolysis could play an integrating role.

If on a traditional technological level the Italian industry appears prepared for the challenge of the Ecological Transition, [9] a sector where Italian products seem weaker today is constituted by high power electrolysis plants, which constitutes a new market space, until now limited to small and medium sizes. Competition over the production of large plants will play a decisive role in reducing production costs.

In the electrolysis sector, many studies have been carried out in the past aimed at the aspect of the efficiency and innovation of the individual components and of the entire system but always in conditions of stable power supply of the electricity source. The current need is instead addressed to other problematic aspects that are still to be explored and considered, more related to the reliability and durability of the equipment in the operating modes that will be provided for these new applications. Frequent and periodic switching on and off operations, as well as operating conditions not under constant load, will pose the need to solve problems relating to management, efficiency and duration. These problems will affect both the electrochemical section of the plants and that of the auxiliaries which, on the other hand, will have to guarantee the quality of the flows entering and leaving the plant (in particular the water and hydrogen treatment). These areas of study and experimentation, which may take place on limited but significant industrial dimensions in the demonstration plants, will have to provide useful information for the final application and the management of stacks and auxiliaries.

In conclusion, the great diffusion of electric renewable increasingly produces an excess of energy on the electricity grid and this overproduction could be used to produce of electrolytic hydrogen with already existing technologies. The priority use of this "green" hydrogen could cover part of the current national industrial demand, thus fulfilling the dual function of reducing carbon dioxide emissions from conventional production processes and providing a method to simplify the management of electric renewables in overload conditions. In parallel or nextly, electricity / gas integration could perform the same function by allowing hydrogen (P2G) to be fed into the network.

The analysis carried out shows that a few large electrolysis plants located where there is and will be an increasing surplus of renewable electricity (mainly in Southern Italy) with many modular electrolysis units could fulfill this function. Inexpensive alkaline electrolysers seem to be preferred for their reliability and durability and for the production of hydrogen at competitive costs.

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