Analysis of Power-to-Gas plant configurations for different applications in the Italian framework

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Abstract: The increase of renewable power production and the need to reduce CO_2 emissions stimulated the smart utilization of electricity for the conversion of CO_2 into valuable feedstocks. Power-to-Gas (P2G) allows to convert and store renewable power into chemical energy (a gaseous fuel), thus favoring the interconnection between the electric and gas grids. There are many potential applications for P2G plants, like gas grid injection, CO_2 methanation, renewable energy storage, transport, as well as several field of applications (i.e. electric grid manager, anaerobic digestion plants, process industries). So, several P2G plant configurations can be designed. Since the economic feasibility assessment could result in very complex evaluations and it is highly influenced by incentives, carbon tax and feed-in tariffs, the paper aims to show the state of the art of P2G design for some of the most interesting applications in the Italian scenario and to identify the most promising solutions, including a preliminary assessment of synthesis gas production costs.

Keywords: Power-to-Gas, hydrogen, CO_2 methanation, LCOE

1. Introduction

More and more carbon dioxide is annually discharged in the atmosphere although the promised targets at international meetings such as in Paris' one in 2015. In fact, an increasing trend of CO_2 emission into the atmosphere has been estimated in 2019, reaching a global value of 36.8 billion tons, i.e. +1.4% respect to 2015 (Global Carbon Project, 2019). Due to the demonstrated connection between CO_2 concentration in the atmosphere and climate change's effects (Anderson et *al.*, 2016), actions have to be taken in order to change the existing trend in the next years. In accordance to the global annual emission data (Global Carbon Project, 2019), energy generation, industrial application and transport contribute, respectively, for the 45%, 23% and 19% of the global CO_2 emissions, while in accordance to Italian statistics, instead, they account, respectively, for the 42%, 19% and 24% (MISE et *al.*, 2020).

Since the energy sector accounts for the highest emissions, renewable energy generation was encouraged by governments in order to substitute traditional fossil fuels. The "*2050 long-term strategy*" was presented by the European Commission to achieve a carbon neutrality by 2050, while the "*Energy and Climate Plan*" (PNIEC) was proposed by the Italian Government aiming to reach almost the 30% of energy production from renewables by 2030. However, due to the intermittent and unpredictable generation of many renewable energy sources (i.e. solar and wind), storage systems are required to effectively integrate such sources in the existing distributing energy systems (Olabi, 2017). The storage issues are particularly relevant for the stability of the electrical grid, since electric grid balancing between energy production and demand is continuously required to avoid electrical transmission and distribution networks failure (Barelli et al., 2015).

Since almost the 55.4% of the Italian electrical energy should be supplied by renewable energy sources in 2030 and since an accumulation potential of 86 ktep/day was estimated by the PNIEC, the storage of renewable power production will become a crucial point to achieve the Italian government target. Electrical batteries were already tested by TERNA S.p.A., which is the Italian Transmission System Operator (TSO), as a possible solution to store the daily excess of electrical energy (Terna, 2017). However, despite the high Technology Readiness Level (TRL), batteries cannot be considered as the unique solution. First of all, batteries production is highly affected by the availability of raw materials (like cobalt), which should be imported from other countries (Song et *al.*, 2019). At the same time, the main worldwide manufacturers of electric batteries are concentrated in few foreign Countries. Therefore, external interferences could strongly affect the Italian electric energy sector. Secondly, a relevant barrier is the disposal of electric batteries, which could have high costs and environmental impact (Meshram, 2020). For these reasons, other storage options have been investigated in the last years.

Power-to-Gas (P2G) is considered as the most promising alternatives to electrical batteries. Based on the conversion of electricity into a fuel (i.e. hydrogen, methane), P2G offers more possibilities than batteries to manage the excess of electrical energy. Since P2G can be considered as a chemical storage of renewable energy into a synthesis fuel, it is possible to guarantee a long term storage if compared to electric batteries, which suffer from discharge phenomena over the time. Moreover, P2G is naturally prepared for a full integration with the gas grid and the transport sectors. Stimulated by P2G potential, SNAM S.p.A., the main Italian gas TSO, organized the Hydrogen Challenge event in 2019 in order to promote the role of hydrogen in the Italian energy scenario. In 2019, two projects dealt with P2G and involving the Authors were financed, i.e. the SuperP2G (“Synergies Utilising renewable Power REgionally by means of Power To Gas”) project (funded by the ERANET European program) and the E-CO2 project (funded by the Emilia Romagna region). In addition to these, in the same year the Italian Ministry of Economic Development (MISE) organized a discussion between interested stakeholders from institutional, research and industrial field resulting in the presentation of other 31 projects containing hydrogen as the main topic.

The paper aims to describe the most promising P2G plant configurations for the Italian scenario in order to help decision makers and stakeholders to evaluate the best option, so to develop a P2G national market. After a preliminary description of P2G processes and of the market state of the art, main plant sections are investigated. Finally, preliminary considerations about economic feasibility of a P2G are reported.

2. Method

In order to analyse possible P2G plant designs an analysis of existing state of the art was performed. Particularly, an in depth literature review of international papers was performed through Scopus database. Due to the extension to the topic, “Power to Gas plants” and “P2G plants” were used as keywords. Other papers were suggested by the SuperP2G project partners. In addition, a market survey of existing technologies was performed for the main plant sections through the direct contact with manufacturers. For the purpose, IEA Task 38, electrolysers and three catalytic methanation manufacturers were directly contacted in order to collect information required to perform technical and economic assessment.

In order to give preliminary considerations concerning the economic feasibility, the Levelized Cost of Energy (LCOE) method was considered as the most appropriate (Short et *al.*, 1995):

$$\text{LCOE} = \frac{TLCC}{\sum Q_n/(1+d)^n} \quad (1)$$

Where TLCC is the total life cycle cost (Short et al., 1995), Q_n is the annual output of the plant, which can be expressed in fuel content (Nm^3 or kg) or energy content (kWh) of gas, while d is the discount rate.

The values in Table 1 are used in the analysis.

Table 1. Assumed values for the economic analysis.

	Value	Unit
Distilled water	3	€/t
Catalyst	90	€/kg
Silica gel	20	€/kg
Adsorbent for H2S removal	320	€/Nm³ biogas h
Alkalyne electrolyser	930	€/kW
Hydrogen tank	50	€/Nm³
Biogas tank	80	€/Nm³
Renewable electricity cost	0,05	€/kWh el
Operative life (N)	20	years
Annual operative hours	4000	h/year
Discount rate (d)	5	%

For the purpose a value of 4000 annual operative hours has been considered as realistic for the future. In fact, even if in a previous work the Authors calculated a value equal to 3500 h/year (Guzzini et al., 2019), the expected penetration of unpredictable renewable sources in Italian energy sector makes the assumption realistic. Furthermore, a quite high discount rate has been suggested by stakeholders to the Authors in order to perform preliminary economic assessments and to account for the risk inherent in a P2G investment (Cigolotti et al., 2019). In the economic assessment revenues are not considered since the scope of the paper is to evaluate the production cost of synthetic fuels from renewable energy. Nevertheless, it must be underlined that, for example, in Italy an incentive of 375€ is added to the actual biogas sale price (12.60 €/MWh at March 2020) every 5 Gcal (1 CIC, Certificate of Release for Consumption), equal to about 64.5 €/MWh for a maximum period of ten years if biomethane is produced by catalytic methanation through renewables.

3. Results and discussion

3.1 Power-to-Gas (P2G): a preliminary state of the art

In Figure 1 a schematic flowchart of P2G processes is reported. Despite the large definition of P2G includes several kinds of processes and final products, in the paper only power-to-hydrogen (P2H) and power-to-methane (P2M) are considered since they resulted as the more diffused and market-ready.

As shown in Figure 1, in the first step water electrolysis allows the dissociation of water into hydrogen and oxygen by means of the renewable power (Ma et al., 2018). The produced hydrogen can be:

- Directly used in chemical, refinery, steel and food industries; an annual hydrogen consumption of around 500.000 ton/year is estimated in Italy (H2IT, 2020).
- Injected into the natural gas network, even if no common international rules exist dealing with the maximum concentration of hydrogen allowed into the grid (Dolci et *al.*, 2019)
- Used in P2M conversion for the production of Synthetic Natural Gas (SNG) through the Sabatier process, which converts H_2 and CO_2 into CH_4 and water (Vogt et *al.*, 2019). SNG can usually substitute traditional natural gas with no injection limitation into the existing natural gas grid.

Pure oxygen, on the other hand, is suitable for specific industrial uses.

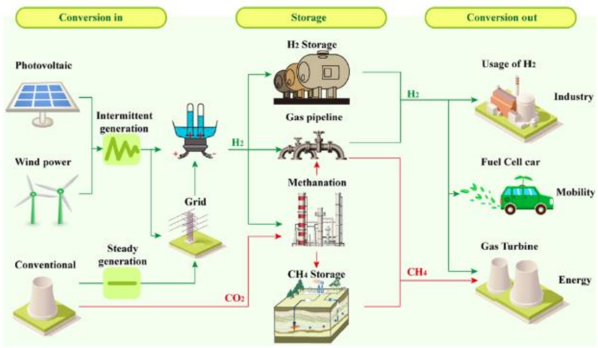

Figure 1. P2H and P2G schematic flowchart. (Ma et al, 2018)

Energy performances can be evaluated through the Sankey diagrams in Figure 2, where typical values for each section are assumed (Shaaf et al., 2014). Only about 50% of the power input is available in the form of SNG at the outlet of the methanation process. In fact, relatively low performances, in the range 62-82%, characterize the commercial electrolysers. However, a greater whole efficiency of almost 80% can be reached if the heat recovery is considered.

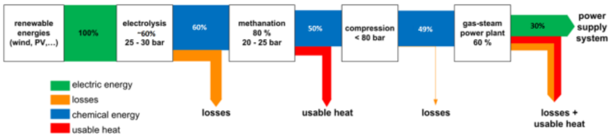

Figure 2. Sankey diagram for a generic P2G plant. (Schaaf et *al.*, 2014)

3.2 Industrial hydrogen production through water electrolysis: analysis of the available technologies

Water electrolysis is the most promising method for efficient production of high purity hydrogen (and oxygen) through the application of a minimum voltage drop between two electrodes, i.e. the cathode (the negative one) and the anode (the positive one) in accordance to the general formula (Eq. 2):

$$2H_2O + \text{electricity} \rightarrow 2H^+ + O_2 \qquad (2)$$

Different electrolysers were designed and tested through the years. Particularly, three configurations can be recognized in literature and classified as i) Alkaline Electrolysis Cell (AEC), ii) Polymer Electrolyte Membrane Electrolysis Cell (PEM) and iii) Solid Oxide Electrolysis Cell (SOEC). (Buttler & Spliethoff, 2018; Sapountzi et *al.*, 2017; Schmidt et *al.*, 2017)

AEC electrolysers represent a mature technology. In fact, more than 24 manufacturers are globally present producing electrolysers with a single stack size up to 6 MW el. From a technological point of view, the two zinc or iron electrodes are immersed in a low temperature (<100°C) and low pressure (≤60 bar) liquid electrolyte (a 25–30% aqueous KOH or NaOH solution) and are separated by a diaphragm, permeable for the passage if OH^- but not for the produced gases. Main advantages of AEC technology are the low capital cost C_0 [€/kW] ($C_0 \approx$2000-700 €/kW for Pel≤2MW, and $C_0 \approx$600 €/kW for greater size), and simpler annual maintenance activity estimated to be less than 1% of the capex.

Since its recent inlet on the market, twelve industrial PEM manufacturers were identified producing electrolysers with a single stack size up to 2 MW el. The PEM electrolysers, instead, ensures a very low cross-permeation, yielding hydrogen with a purity higher than that allowed by AEC, and typically greater than 99.99% after drying process. PEM electrolysers consist of a compact module design due to the solid electrolyte and high current density operation compared to AEC. This supports their high-pressure (≤100 bar) and high temperature (≤100 °C) operation. A proton exchange membrane (usually a Nafion® membrane) is installed to separate the high pressure produced gases while the noble metals electrodes are used for the aggressive and corrosive conditions involved in the PEM assembly. This, together with the high cost of polymeric membranes, is the main limitation for the commercialization of PEM electrolysis in the near term. In accordance to the lower number of device in the market respect to AEC, a higher C_0 is estimated ($C_0 \approx$3400-1200 €/kW for $P_{el} \leq$2 MW). Due to the greater operative pressure, higher failure rates and more complex and long maintenance procedures are expected respect to AEC.

Only one industrial SOEC manufacturer was found in Germany. SOEC electrolysers operates at temperatures of 700–900°C, with water in the form of steam. The high operating temperature ensures high electrolysis efficiency even if a high temperature source is required for the production of steam. Therefore, a lower total efficiency than AEC and PEM can be reached if heating demand is ensured by traditional fuels. Once the required heat is instead a renewable or a waste heat, the scenario changes. However, very few information is available on the technology resulting very difficult to technically and economically assess industrial application.

A brief summary of the main parameters for each technology is reported in Table 2.

Table 2. Review of the main technical parameters for the three possible type of electrolysers.

Parameter	AEC	PEM	SOEC
Technological maturity	High	Low/medium	Development phase
Electrolyte	Alkaline solution	Solid polymeric membrane (Nafion)	Ceramic ZrO_2 drugged with Y_2O_3
Ionic agent involved	OH^-	H_3O^+ / H^+	O_2^-
Temperature [°C]	40 – 90	20 – 100	600 – 1000
Pressure, [bar]	< 30	< 100	Not available
Efficiency, [%]	59 – 70	65 – 82	Not available
Investment, [k€/kW]	0.5 - 2	1.3-3.5	Not available
Maintenance	Simple 1% of C_0	Complex > 1% of C_0	Not available

3.3 Industrial hydrogen storage: analysis of the available technologies

Large scale storage of hydrogen represents a critical aspect of plant design. Based on the review of (Andersson & Gronkvist, 2019), hydrogen storage technologies are classified in three main categories, i) physical storage, ii) adsorption and iii) chemical storage as shown in Figure 3. Storage of pure hydrogen as a compressed gas up to 700 bar, $H_2(g)$, or into a liquid phase, $H_2(l)$, are the only means currently applied to store hydrogen at a significant scale. Respect to physical storage, adsorption and chemical storage into metal or chemical hydrides (ammonia, methanol, etc.) are not still fully mature technologies and so ready for application at industrial scale.

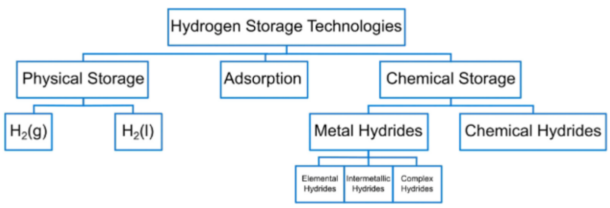

Figure 3. Preliminary classification of the available hydrogen storage technologies. (Andersson & Gronkvist, 2019).

A preliminary analysis can be performed based on the volumetric storage densities, electric and thermal energy demand. A summary of literature data is reported in Table 3: greater storage density can be possible through chemical hydrides in which hydrogen is chemically bonded with lighter elements to produce ammonia, methanol or other liquid substances. A lower density is achieved by metal hydrides and adsorption. Respect to commercial technologies, greater storage density is reached by liquefaction even if a great electrical energy demand is needed to reach fluid inversion temperature, i.e. 200.15 K. In addition to electrical, also thermal energy demand can be present both in hydrogen storing and/or realising in order to create or destroy the bonds in metal and chemical hydrides. Particularly, exothermic reactions usually verify during storage process in a temperature range between 70-350°C (metal hydrides) and 100-400°C (chemical hydrides) resulting possible to recover the waste heat increasing total efficiency. Due to the endothermal reaction, thermal energy is required to release hydrogen. Furthermore, a slightly higher temperature is present in most cases respect to that in the charging phase.

Table 3. Summary of the main characteristics for hydrogen storage technologies. For thermal demand only endothermal release reactions are considered.

Hydrogen storage technology	**Storage density [kg_{H2}/m^3]**	**Electric demand, [kWh/kg_{H2}]**	**Thermal demand, [kWh/kg_{H2}]**
Physical storage: H2(g)	10 - 40	1 – 1.6	/
Physical storage: H_2(l)	70	6	/
Adsorption	50	6.7	/
Metal hydrides	40 – 85	0.8-10	1-10.6
Chemical hydrides	55 – 125	0.7-6.7	4.2-11.2

3.4 Industrial chemical methanation of hydrogen and carbon dioxide: analysis of the available technologies

Even if known from many years, the interest in the chemical methanation increased only in the recent years. Methane and water are produced from hydrogen and carbon dioxide in accordance to the following exothermic chemical reaction (Sabatier's reaction):

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \quad (3)$$

In accordance to the Le Châtelier criterion, high operative pressure and low temperature should be ensured to improve methane formation. In fact, several other chemical reactions occur in addition to Eq. 3 in presence of hydrogen and carbon dioxide and specific thermodynamic conditions (Gotz et *al.*, 2016).

During the years three main reactor configurations (adiabatic, isothermal and polytropic) were developed as a function of the internal temperature profile (Table 4). In adiabatic reactors, no external cooling is performed requiring other solutions to control the operative temperature such as gas recirculation or the introduction of inert media. In isothermal reactors, a temperature lower than previous case is achieved resulting in slower reaction rates. In polytropic reactors, instead, operative temperatures are between those of other two types, allowing an easier control and satisfactory performances. From a design point of view, different solutions were developed as fixed bed reactors, fluidized bed reactors and structured reactors as shown in Figure 4. Only fluidized bed reactors are characterized by a sufficient TRL for commercial applications.

Table 4. Summary of methanation reactors main parameters.

Operation mode	**Adiabatic**	**Polytropic**	**Isothermal**
Reactor stages	2-7	1-2	1-2
Gas recycling	Usually	Sometimes	Sometimes
Temperature range, [°C]	250-700	250-500	300-400
Reactor costs	Medium	High or very high	Low or medium
TRL	9	4-7	4-7

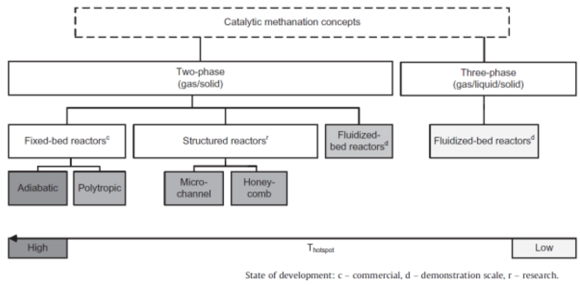

Figure 4. Available different design for methanation. In the figure internal hotspot temperature and state of development are also reported. (Rönsch et *al.*, 2016).

The methanation process can be further divided into three main categories based on the source of CO_2 stream: the first one is linked to the methanation of any carbon dioxide source; the second concerns the upgrading of biogas, allowing to obtain biomethane from biogas; the third is linked to the upgrading of syngas, a gas produced by the biomass or coal gasification process.

3.5 Outlook of the existing P2H and P2M plants

Fifty-six P2H and thirty-eight P2M plants were active in 2019 in the world with a total electric installed capacity of 24.1 MW and 14.5 MW respectively. More than 6200 m^3/h and 590 m^3/h of hydrogen and SNG are currently produced resulting in an average efficiency of 77% and 41%. A low value for P2G is found due to the fact that waste heat recovery is usually not considered in the comparison (Thema et *al.*, 2019). The location of P2H and P2G plants in the world is shown in Figure 5.

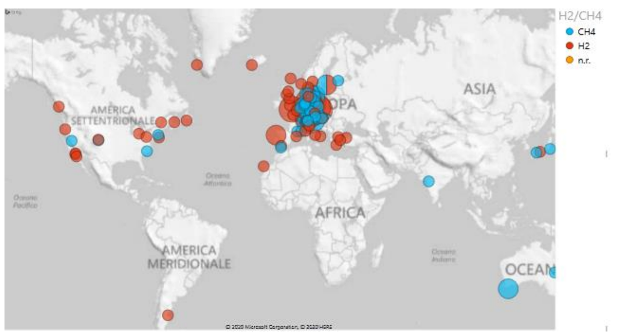

Figure 5. Location of P2H and P2G plants in the world. Data elaboration from (Thema et *al.*, 2019)

3.6 Possible P2G configurations and preliminary economic evaluations

3.6.2 P2H plant configuration

P2H plants simply require renewable electricity and water in order to produce hydrogen through water electrolysis. In Figure 6 a possible plant configuration is shown. In particular, physical gas storage is represented. However, the other storage technologies explained in section 3.3 are also possible. In addition, all the electrolyser's technologies described in section 3.2 can be integrated in the proposed plant configuration. Finally, three possible potential applications are considered for hydrogen: i) injection into the natural gas grid, ii) fuel for transport sector and iii) use as raw material for industrial processes. No further details are given about plant configurations at final end-users since it is out of the scope of the paper.

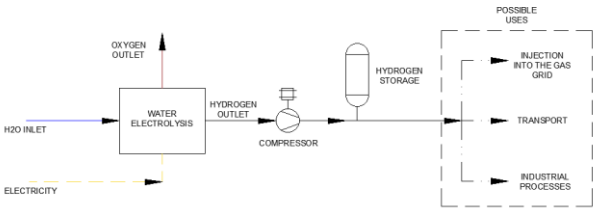

Figure 6. P2H plant configuration.

Due to P2H potential respect to grid balancing, LCOE was calculated in order to evaluate the economic feasibility. Since different sizes and electrolyser's technologies can be implemented depending on the specific application, LCOE was analysed for AEC and PEM electrolysers (Figure 7). As shown in Figure 7, due to lack of reliable data, LCOE for PEM electrolysers was calculated up to 2 MW el. Furthermore, AEC's trend changes at 2 MW el, since it is the threshold between single and multi-stack configuration. However, electrolyser's size does not seem to influence LCOE above 2 MW el. Therefore, a production cost of about 0.12-0-15 €/kWh can be computed for industrial applications, depending on electrolysis process efficiency.

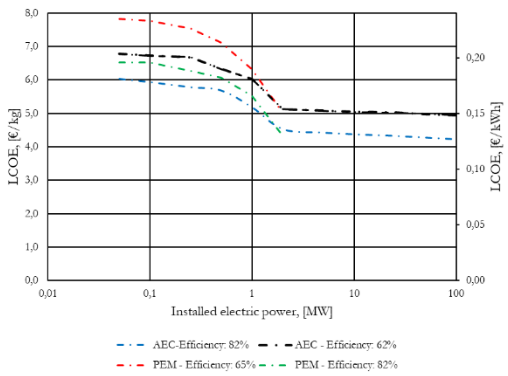

Figure 7. LCOE for hydrogen production expressed in [€/kg] and [€/kWh].

3.6.1 P2M plant configurations

P2M plants require renewable electricity and a source of carbon dioxide for the operation. For this reason, carbon dioxide from industrial processing waste, from combustion discharges or from other fermentation processes can be used. Untreated SNG cannot usually be injected directly into the networks due to the CO_2 and H_2 content higher than allowed. Therefore, SNG treatment processes have to be considered. Three main different configurations have been proposed in literature. In the first two, carbon dioxide comes through a biogas stream while in the third one carbon dioxide is recovered by industrial processes.

The first one consists of two methanation reactors (Figure 8). Before entering the methanation reactors, the raw biogas flow is purified from hydrogen sulphide, organic sulphur and siloxanes to protect the catalyst. H_2 and O_2 are produced by electrolysis and stored at a high pressure into storage tanks. Purified biogas is stored in a tank that will contain methane percentages between 55-65% and CO_2 percentages between 45-35%. The stream of H_2 and biogas is heated up to 250°C and is mixed with steam, which is added to avoid the formation of carbon residues into the reactors. The SNG is then purified through the adsorption mechanism and it is finally injected into the networks. An efficiency up to 59% is calculated even if higher performances can be achieved by heat recovery.

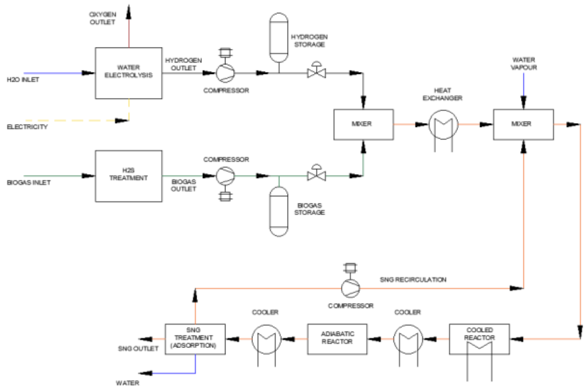

Figure 8. First possible configuration.

Concerning economic considerations, a total investment of 4.29 M€ is estimated for a plant able to consume up to 200 Nm^3/h of biogas with a total production of 200 Nm^3/h of SNG. Annual costs are estimated equal to 600 k€/year. From these values a LCOE equal to 0.23 €/kWh results.

In the second configuration only a single cooled methanation reactor is implemented resulting in a simpler design and smaller footprint, even if more compressors are required especially for SNG treatment process (Figure 9).

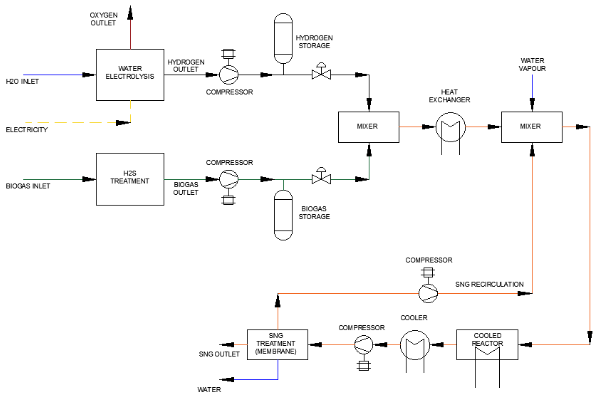

Figure 9. Second proposed configuration for P2G in Italy.

With respect to the previous configuration of Figure 8, however, due to the lower number stage of methanation, more residues (in particular hydrogen) are present in product stream requiring more complex treatment process of the SNG produced. For the purpose, membrane separation mechanism is required to achieve the desired methane concentration.

A methanation efficiency up to 55.5% is calculated even if greater values are also in this case possible thank to heat recovery. Concerning economic considerations, a total investment of 4.34 M€ is estimated for a plant able to be supplied with up to 200 Nm^3/h of biogas with a total production of 200 Nm^3/h of SNG. Annual costs are estimated equal to 870 k€/year. From these values a LCOE equal to 0.30 €/kWh results.

In the third configuration (Figure 10), a CO_2 separation unit is required in order to recover carbon dioxide from flue gases for the following methanation reaction. More than two stages of methanation reactions are usually present in order to reach the highest conversion efficiencies as possible. In order to limit the operative temperature in the first reactor, outputs are cooled and in part recirculated upstream into the mixer. An efficiency up to 56% is assessed without considering possible heat recovery.

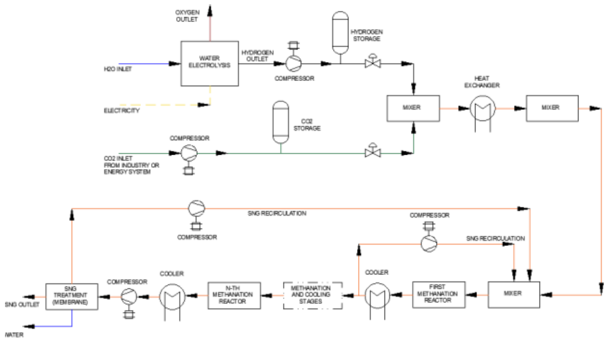

Figure 10. Third proposed configuration for P2G in Italy.

Concerning economic considerations, a plant size able to elaborate 250 ton/day of CO_2 is considered the best choice for the Italian industrial and energy market. A maximum production of almost 4400 Nm^3/h of SNG is estimated. For the purpose a total investment of 290 M€ is expected. Annual costs are estimated equal to 38 M€/year. From these values a LCOE equal to 0.67 €/kWh is calculated.

4 Conclusions

The implementation of P2G plants would ensure several benefit to the Italian energy sector. First of all, due to the growing electricity production from renewables, an always greater storage capacity is expected in order to balance the electric grid. P2G can convert the surplus of electricity into hydrogen or SNG. Due to its extension (Bianchini et. al., 2015), in fact, the Italian gas network can be considered as a potential energy storage infrastructure. However, SNG production should be preferred since limits to hydrogen injection in the natural gas grid are currently present. In fact, several concerns are still unsolved about P2H possible impact on the existing infrastructures in terms of safety (Bianchini et *al.*, 2018a) and on the installed devices fed by natural gas (Deymi-Dashtebayaz et *al.*, 2019; Bianchini et *al*, 2018b). P2M seems to be preferable from this perspective. Moreover, since CO_2 is consumed in the Sabatier’s process, P2M contributes to reduce CO_2 emissions in the atmosphere. Plant solutions tailored on the Italian industrial and energy sectors were proposed. In fact, based on a market analysis, one configuration for P2H and three possible configurations for P2M were shown.

However, although the benefits related to a better exploitation of renewable sources and the positive impact on the environment, economic and regulative barriers still restrain the market uptake of P2G. Due to the low number of industrial projects, in fact, very high investments are required. Furthermore, no sufficient rewarding policies seem to be present resulting in high production cost. A hydrogen production cost via P2H of about 4-5 €/kg has been estimated, which is still greater than the value reported for other traditional technologies (1.5-3 €/kg) such as, for example, but not limited to natural gas steam reforming (IEA, 2019).

With respect to P2M if compared with the current cost of natural gas in the Italian gas market in the years 2018-2019 (13.21-19.15 €/MWh) (GME, 2020), the SNG produced via CO_2 methanation of raw biogas seems very promising, since the production costs of 23-30 €/MWh estimated in the paper is not far from market price of natural gas. On the other hand, the application of P2M in biogas plants is a niche market, while if CO_2 separation from a flue gas is needed, the resulting production cost of SNG results as up to five-six times expensive than natural gas.

From an economic comparative analysis, therefore, P2H result more competitive with respect to P2M in terms of energy production cost, i.e. €/kWh. However, as reported at the beginning, several barriers at production and customers’ side still hinder the complete market uptake. In addition, no environmental benefits would be possible in terms of CO_2 emissions reduction as occurred in P2M plants.

The consequence is that incentives are fundamental to ensure the economic acceptance of the investment, and so dedicated rewarding policies, like carbon tax or feed-in tariff, that will be assessed in a future work by the Authors, are required to increase the economic sustainability of P2G.

References

Anderson, T.R., Hawkins, E. Jones, P.D. (2016). CO2, the greenhouse effect and global warming: from the pioneering work of Arrhenius and Callendar to today's Earth System Models. *Endeavour*. Vol. 40, pp. 178-187.

Andersson, J., Gronkvist, S. (2019). Large-scale storage of hydrogen. *International Journal of Hydrogen Energy*. Vol. 44, pp. 11901-11919.

Barelli, L., Desideri, U., Ottaviano, A. (2015). Challenges in load balance due to renewable energy sources penetration: The possible role of energy storage technologies relative to the Italian case. *Energy*. Vol. 93, pp. 393-405.

Bianchini, A., Donini, F., Guzzini, A., Pellegrini, M., Saccani, C. (2015). Natural gas pipelines distribution: Analysis of risk, design and maintenance to improve the safety performance. *XX Summer School 'Francesco Turco' - Industrial Systems Engineering*. Naples, pp. 243–248.

Bianchini, A., Guzzini, A., Pellegrini, M., Saccani, C. (2018). Natural gas distribution system: A statistical analysis of accidents data. *International Journal of Pressure Vessels and Piping*. Vol. 168, pp. 24–38.

Bianchini, A., Guzzini, A., Pellegrini, M., Saccani, C. (2018). Gas smart metering in Italy: state of the art and analysis of potentials and technical issues. *XXIII Summer School "Francesco Turco" – Industrial Systems Engineering*. Palermo.

Buttler, A., Spliethoff, H. (2018). Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*. Vol. 82, pp. 2440-2454.

Cigolotti, V., McPhail, S.J., Tammasino, M.C. Hylay. National Policy Paper – Italy. Deliverable 3.5 of the project HyLaw.

Deymi-Dashtebayaz, M., Ebrahimi-Moghadam, A., Pishbin, S.I., Pourramezan, M. (2019). Investigating the effect of hydrogen injection on natural gas thermo-physical properties with various compositions. *Energy*. Vol. 167, pp. 235-245.

Dolci, F., Thomas, D., Hilliard, S., Guerra, C.F., Hancke, R., Ito, H., Jegoux, M., Kreeft, G., Leaver, J., Newborough, M., Proost, J., Robinius, M., Weidner, E., Mansilla, C., Lucchese, P. (2019). Incentives and legal barriers for power-to-hydrogen pathways: An international snapshot. *International Journal of Hydrogen Energy*. Vol. 44, pp. 11394-11401.

Global Carbon Project (2019). *Global carbon budget*. [Online]. Available:https://www.globalcarbonproject.org/carbonbudget/19/files/GCP_CarbonBudget_2019.pdf

Götz, M., Lefebvre, J., Mörs, F., Koch, A.M, Graf, F., Bajor, S., Reimert, R., Kolb, T. (2016). Renewable Power-to-Gas: A technological and economic review. *Renewable Energy*. Vol. 85, pp. 1371-1390.

GME (2020). Dati di sintesi MGP-GAS. [Online]. Available:http://www.mercatoelettrico.org/It/Statistiche/Gas/StatMGP-GAS.aspx

Guzzini, A., Bianchini, A., Pellegrini, M., Saccani, C. *Analysis of the existing barriers and of the suggested solutions for the implementation of Power to Gas (P2G) in Italy*. Presentation at the 5th International Conference on Smart Energy Systems Copenhagen, 10-11 September 2019.

H2IT (2019). *Piano Nazionale di Sviluppo: Mobilità idrogeno Italia*. Chapter 2, pp. 21. [Online]. Available: https://www.h2it.it/wp-content/uploads/2019/12/Piano-Nazionale_Mobilita-Idrogeno_integrale_2019_FINAL.pdf

IEA (2019). *The future of hydrogen. Seizing today's opportunities*. Chapter 2. IEA. Paris (France).

Ma, J., Li, Q., Kühn, M., Nakaten, N. (2018). Power-to-gas based subsurface energy storage: A review. *Renewable and Sustainable Energy Reviews*. Vol. 97, pp. 478-496.

Meshram, P., Mishra, A., Abhilash, Sahu, R. (2020). Environmental impact of spent lithium ion batteries and green recycling perspectives by organic acids – A review. *Chemosphere*. Vol. 242.

MISE, MATMM, MIT (2019). *Piano Nazionale Integrato per l'Energia e il Clima*. Pag. 47. Roma. Italia.

Olabi, A.G. (2017). Renewable energy and energy storage systems. *Energy*. Vol. 136, pp. 1-6.

Rönsch, S., Schneider, J., Matthischke, S., Schlüter, M., Götz, M., Lefebvre, J., Prabhakaran, P., Bajohr, S. (2016). Review on methanation – From fundamentals to current projects. *Fuel*. Vol. 166, pp. 276-296.

Sapountzi, F.M., Gracia, J.M., Weststrate, C.J.K.-J., Fredriksson, H.O.A., Niemantsverdriet, J.W.H. (2017). Electrocatalysts for the generation of hydrogen, oxygen and synthesis gas. *Progress in Energy and Combustion Science*. Vol. 58, pp. 1-35.

Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., Few, S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. *International Journal of Hydrogen Energy*. Vol. 42, pp. 30470-30492.

Schaaf, T., Grünig, J., Schuster, M.R., Rothenfluh, T., Orth, A. (2014). Methanation of CO2 - storage of renewable energy in a gas distribution system. *Energy, Sustainability and Society*. Vol. 4.

Short, W., Packey, D., Holt, T. (1995). *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technology*. Chapter 4, pp. 47-50. National Renewable Energy Laboratory. Golden (Colorado).

Song, J., Yan, W., Cao, H., Song., Q., Ding, H., Lv, Z., Zhang, Y., Sun, Z. (2019). Material flow analysis on critical raw materials of lithium-ion batteries in China. *Journal of Cleaner Production*. Vol. 215, pp. 570-581.

Terna (2017). Rapporto pubblico anno 2016. Storage Lab. Sperimentazione di progetti pilota di accumulo energetico di tipo power intensive. [Online]. Available: https://download.terna.it/terna/0000/0934/80.PDF.

Thema, M., Bauer, F., Sterner, M. (2019). Power-to-Gas: Electrolysis and methanation status review. *Renewable and Sustainable Energy Review*. Vol. 112, pp. 775-787.

Vogt. C., Monai, M., Kramer, G.J., Weckhuysen, B.M. (2019). The renaissance of the Sabatier reaction and its applications on Earth and in space. *Nature Catalysis*. Vol. 2, pp. 188-197.