XXV Summer School Francesco Turco

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

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Introduction

State of the art of Power to Gas (P2G)

Possible P2G configurations and preliminary economic evaluations

Future developments and conclusions

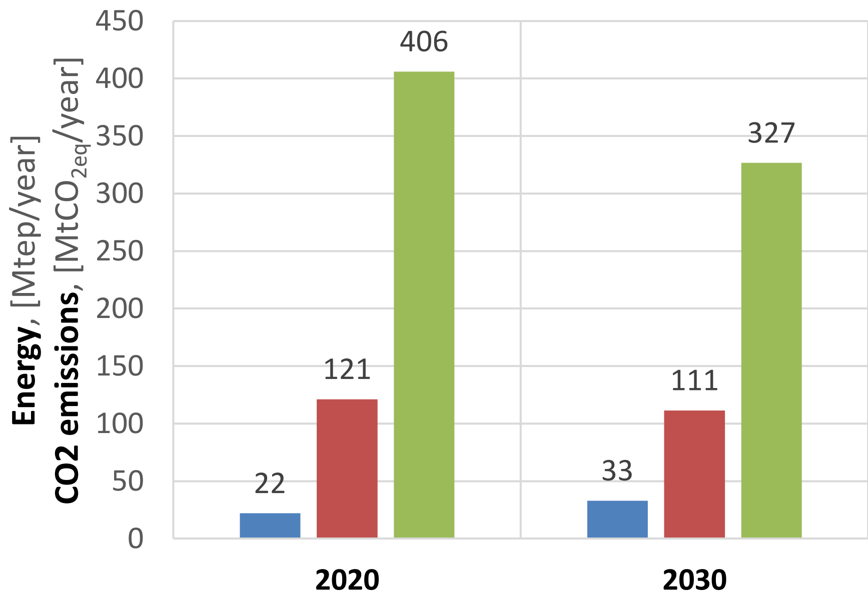
INTRODUCTION

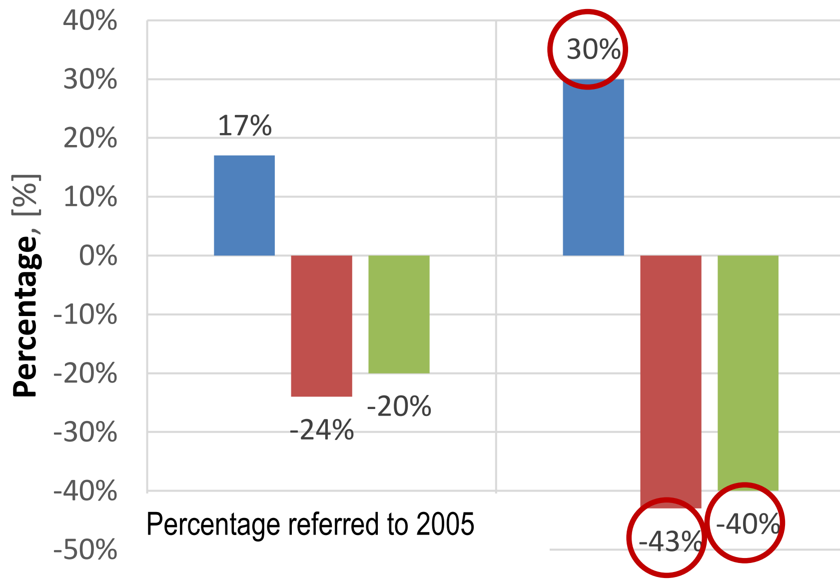
In 2019, the Energy and Climate Plan was proposed to define Italian energy strategy within 2030

Three main pillars are identified:

1. *Increase of renewables in final energy consumption*
2. *Increase of efficiency in energy utilisation*
3. *Carbon Dioxide emissions reduction*

ENERGIA CLIMA 2030





An increase demand of flexibility and storage capacity is expected

TARGET = Increase of renewable energy consumption – up to 33 Mtep/year

Energy balance:

$\alpha \times E_{el,tot} = \int_0^{365} \int_{t_1}^{t_2} P_{ren}(t)dt\,dy \rightarrow$ up to the 55,4% of the Italian energy consumption in 2030 has to be covered by renewable energy sources. As a result, the already reached increase of renewable power sources connected to the grid is moving towards a “renewable electrical networks”.

Such a huge transformation should be accompanied by the development of new solutions for the Italian electric grid management to avoid grid congestion caused by the rising unpredictability of renewable

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A mix of conventional and innovative solutions are necessary to manage the increase of renewable plants such as, for example, the smart grids and **energy storage plants** (up to 1 TWh/day).

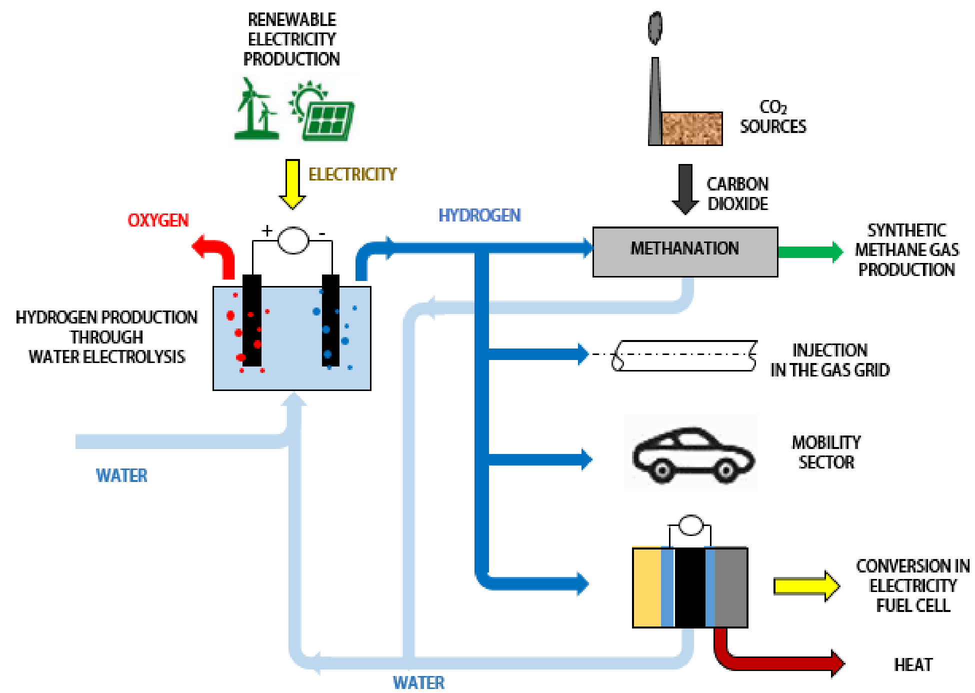
So the paper aims to investigate Power to Gas as possible approach for Italian energy storage demand

What is Power to Gas?

Power to Gas ensures the **connection between electrons and molecules**, converting the surplus electric power in gaseous fuel, such as hydrogen through **water electrolysis**.

Several purposes can be considered for the hydrogen produced by water electrolysis:

1. Converted in Synthetic Natural Gas (SNG) though methanation process
2. Directly injected into the natural gas network
3. Used as fuel in the transport sector
4. Converted back into electricity and heat by fuel cells
5. Directly used as raw material for industrial processes



Hydrogen from water electrolysis:

$$2H_2O + \mathbf{Electricity} \rightarrow 2H_2 + O_2$$

Synthetic Natural Gas (SNG):

$$H_2 + CO_2 \rightarrow CH_4(Syngas) + 2H_2O$$

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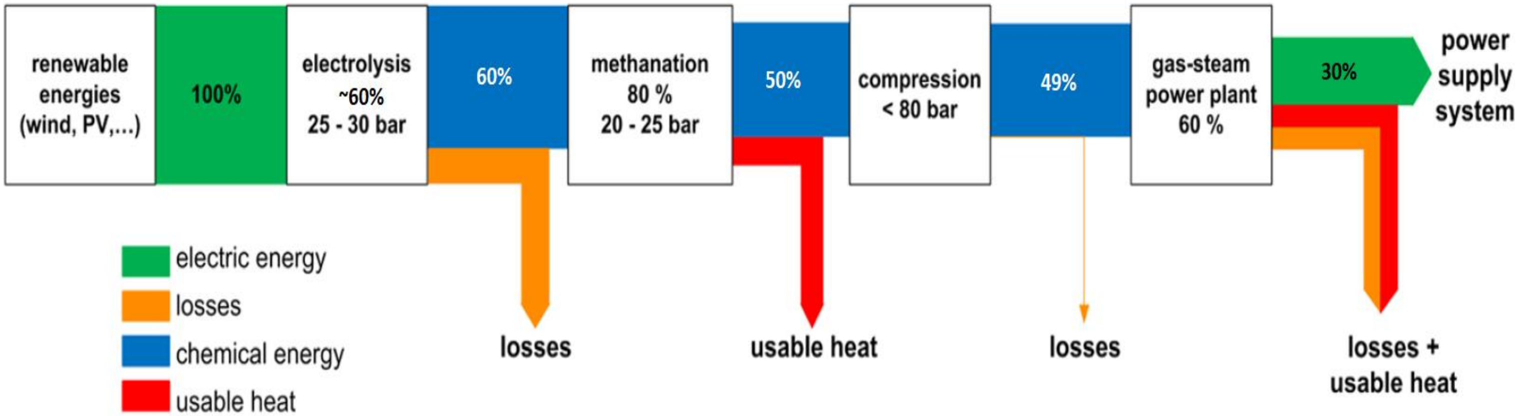
What is the whole efficiency of P2G?

Power to Gas efficiency is relatively low compared to alternative technologies since several energy losses occur in the whole process. Therefore, solutions for energy recovery are required to make P2G competitive with traditional technologies.



Sankey diagram for a generic P2G plant. (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)

COMPARISON WITH COMPETITIVE SOLUTIONS	
Technologies	**Efficiency**
P2H (only hydrogen production)	60% – 70%
Steam reforming	65% – 75%
P2H (conversion of hydrogen into electricity)	33% - 42%
Electric battery	60% - 88%
CAES	70% – 90%
PSH	70% - 82%

References

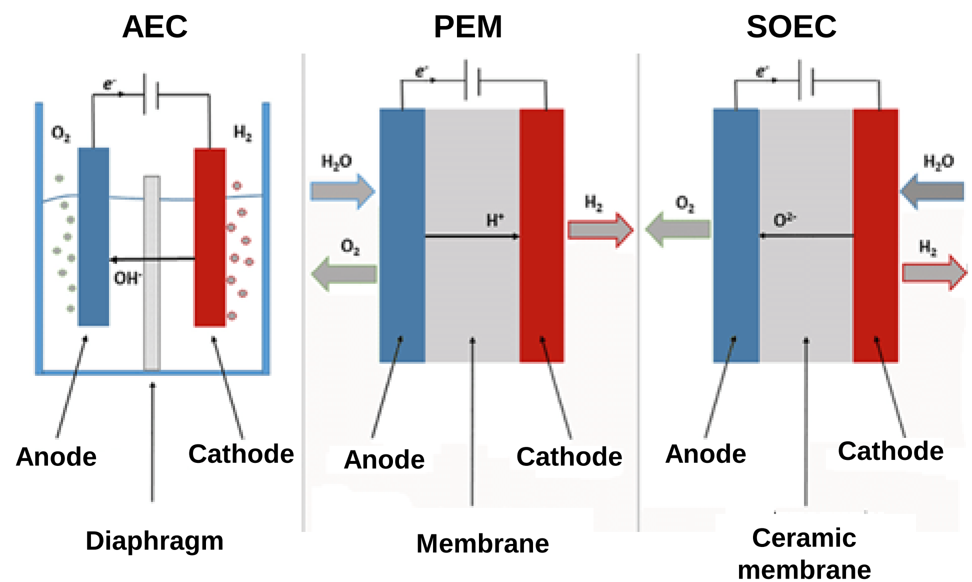
Cormos, A.-M.; Szima, S.; Fogarasi, S.; Cormos, C.-C. *Economic Assessments of Hydrogen Production Processes Based on Natural Gas Reforming with Carbon Capture*. In Proceedings of the Chemical Engineering Transactions; 2018; Vol. 70, pp. 1231–1236

Zakeri, B.; Syri, S. *Electrical energy storage systems: A comparative life cycle cost analysis*. Renew. Sustain. Energy Rev. 2015, 42, 569–596

Water electrolysis process

Water electrolysis is the most promising method for efficient production of high purity hydrogen through the application of minimum voltage drop between two electrodes, i.e. the cathode (the negative one) and the anode (the positive one). At the state of the art three different technologies for water electrolysis:

- Alkaline electrolisers (AEC)
- Proton Exchange Membrane electrolisers (PEM)
- Solid Oxide electrolisers (SOEC)



Parameter	AEC	PEM	SOEC
Technological maturity	High	Low/medium	Development phase
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

Note: Since SOEC is still in a development phase, several information are currently not available at the state of the art

CATHODE		
$H_2O + 2e^- \rightarrow 2OH^- + H_2$	$2H^+ + 2e^- \rightarrow H_2$	$H_20 + 2e^- \rightarrow H_2 + O^{2-}$
ANODE		
$2OH^- \rightarrow H_2O + ½O_2 + 2e^-$	$H_20 \rightarrow 2H^+ + ½O_2 + 2e^-$	$O^{2-} \rightarrow ½O_2 + 2e^-$

References:

Foteini M. Sapountzi, Jose M. Gracia, C.J. (Kees-Jan)Weststrate, Hans O.A. Fredriksson, J.W. (Hans) Niemantsverdriet, Electrocatalysts for the generation of hydrogen, oxygen and synthesis gasProgress in Energy and Combustion Science, 58 (2017) 1 – 35;

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

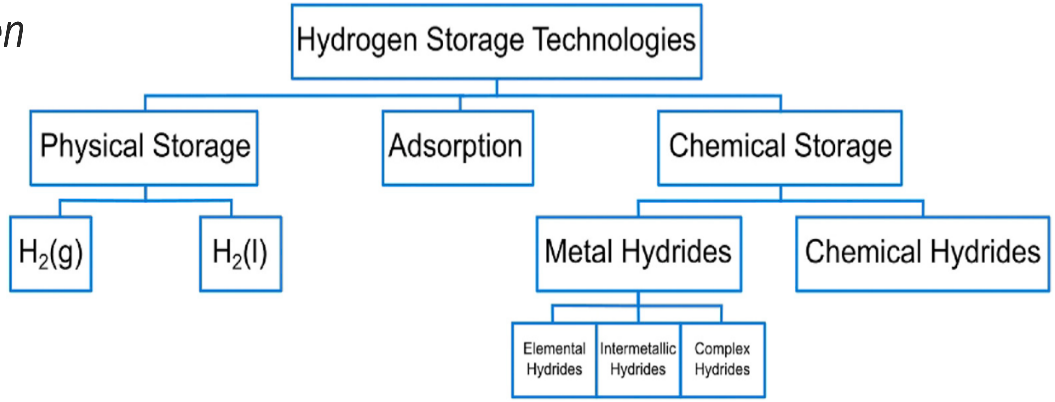
Alexander Buttlera, Hartmut Spliethoff. *Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review*. Renewable and Sustainable Energy Reviews, 82 (2018) 2440 – 2454;

Hydrogen storage solutions

Large scale storage of hydrogen represents a critical aspect of plant design. Based on (Andersson & Gronkvist, 2019), hydrogen storage technologies are classified in three main categories:

i) Physical storage: pressurized and liquefied hydrogen
ii) Adsorption
iii) Chemical storage: metal and chemical hydrides

However, only phisical storage is market ready.



Hydrogen storage technology	Storage density [kWh/m^3]	Electric demand, [kWh/kg_{H2}]	Thermal demand, [kWh/kg_{H2}]
Physical storage: H2(g)	15 @5 bar 200 @70 bar 1000 @ 300 bar	1 – 1.6	/
Physical storage: H_2(l)	2300	6	/
Adsorption	1600	6.7	/
Metal hydrides	1350 – 2850	0.8-10	1-10.6
Chemical hydrides	1850 – 4150	0.7-6.7	4.2-11.2

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

Note: 1 kg of hydrogen is equivalent to 120.000 kJ of energy, i.e. ≈ 30 kWh

Chemical methanation of hydrogen and carbon dioxide

Methane and water are produced from hydrogen and carbon dioxide in accordance to the following exothermic chemical reaction, known as the Sabatier's reaction:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

Three main reactor configurations were developed:

1. *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.
2. *Isothermal reactors*, external cooling is performed ensuring a temperature lower than the previous case.
3. *In polytropic reactors*, instead, operative temperatures are between those of other two types, allowing an easier control and satisfactory performances.

Configuration	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

References:

Stefan Rönsch, Jens Schneider, Steffi Matthischke, Michael Schlüter, Manuel Götz, Jonathan Lefebvre, Praseeth Prabhakaran, Siegfried Bajohr. 2016. *Review on methanation – From fundamentals to current projects*. Fuel, 166, pp. 276-296.

Karim Ghaiba, Fatima-Zahrae Ben-Fares. 2018. *Power-to-Methane: A state-of-the-art review.* Renewable and Sustainable Energy Reviews. 81, pp. 433-446.

Manuel Götz, Amy McDaniel Koch, Frank Graf. 2014. *State of the Art and Perspectives of CO2 Methanation Process Concepts for Power-to-Gas Applications*. International Gas Conference

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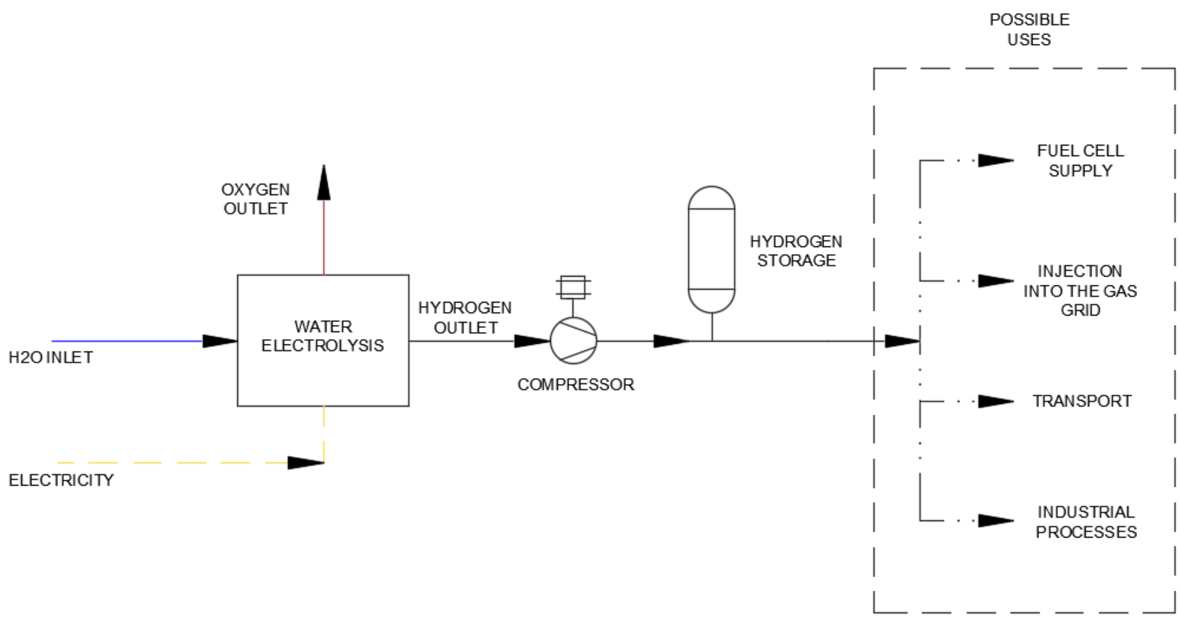
Possible P2G configurations for Italian framework

What is the best solution for P2G in Italy? The answer to the question is not trivial and some considerations have to be performed

First solution: *Power to Hydrogen*
The first plant solution involves the production of hydrogen that can directly injected into the gas network (up to a concentration of $10\%_{vol}$), used in transport sector or to supply part of the Italian industrial demand (560,000 ton/year).



Technology	Hydrogen cost, [€/kg]
Power to Hydrogen	2,5 – 6,4
Steam methane reforming	0,8 – 2,7
Steam methane reforming with Carbon Capture and Utilization	1,3 – 2,5
Coal gasification	1,0 – 1,9

Source:
Hydrogen production costs by production source, 2018.
https://www.iea.org/data-and-statistics/charts/hydrogen-production-costs-by-production-source-2018

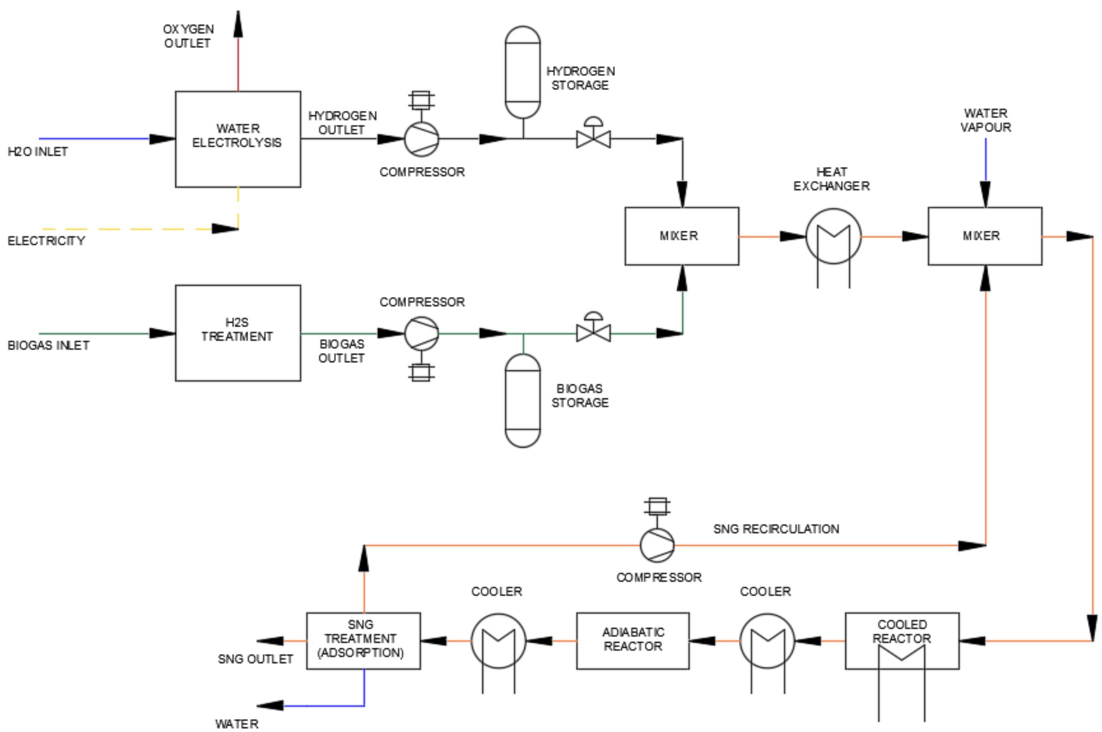
Possible P2G configurations and preliminary economic evaluations

Possible P2G configurations for Italian framework

Second solution: Power to Methane (P2M)

P2M plants require renewable electricity and a source of carbon dioxide for the operation taken, for example, from industrial processing waste, combustion discharges or other fermentation processes. In addition, the Synthetic Natural Gas (SNG) cannot be directly injected into the networks but an upgrading is required.

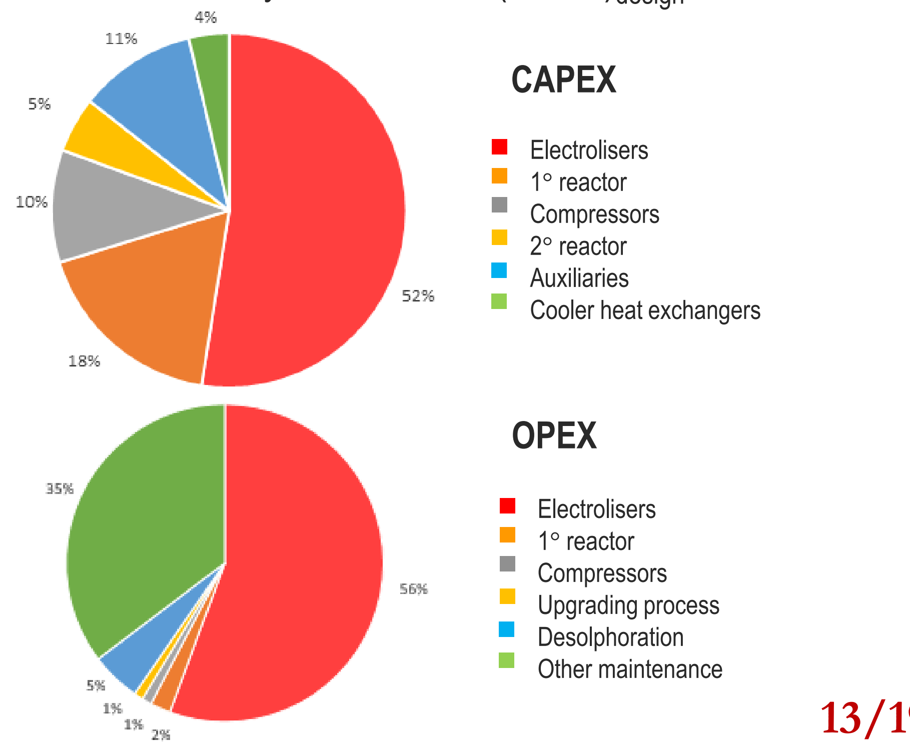
First configuration:



Efficiency: up to 59%

CAPEX: 4,3 M€ for 200 Nm3/h → 21,5 k€ / $(Nm^3/h)_{design}$

OPEX: 600 k€/year. → 3 k€ / $(Nm^3/h)_{design}$



Possible P2G configurations for Italian framework

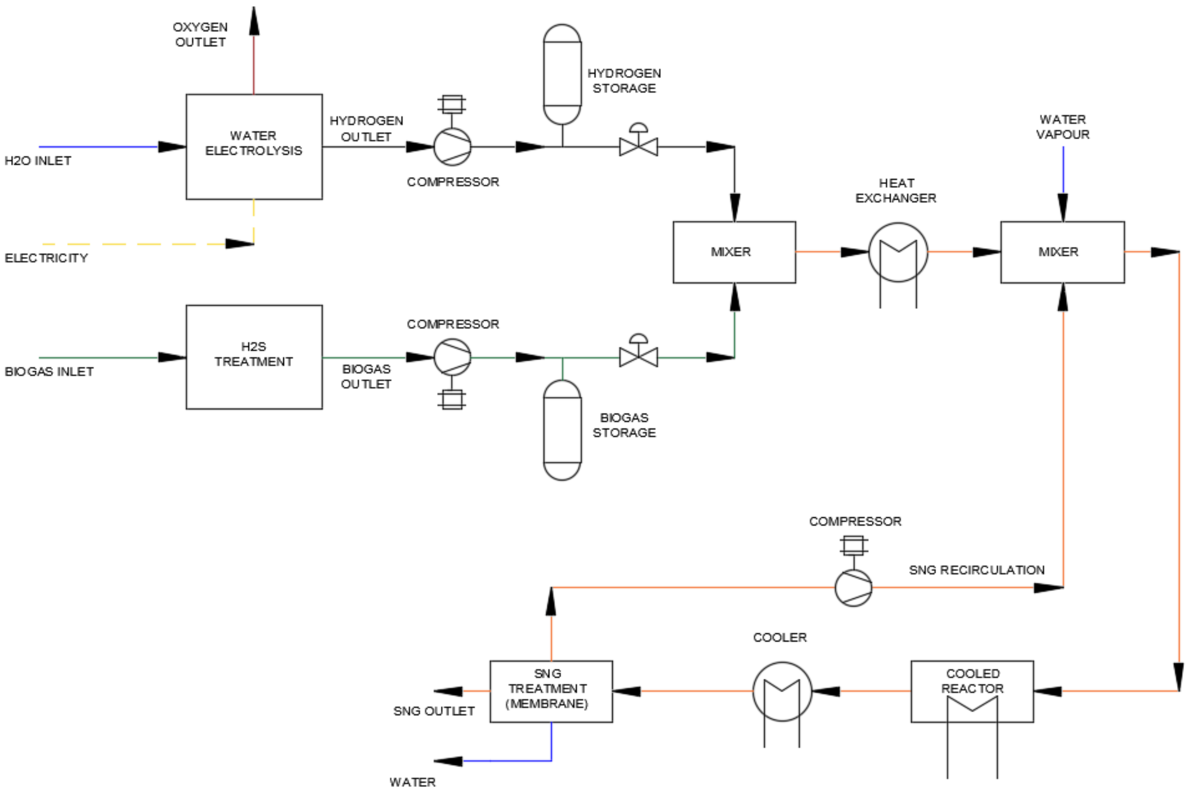
Second solution: Power to Methane (P2M)

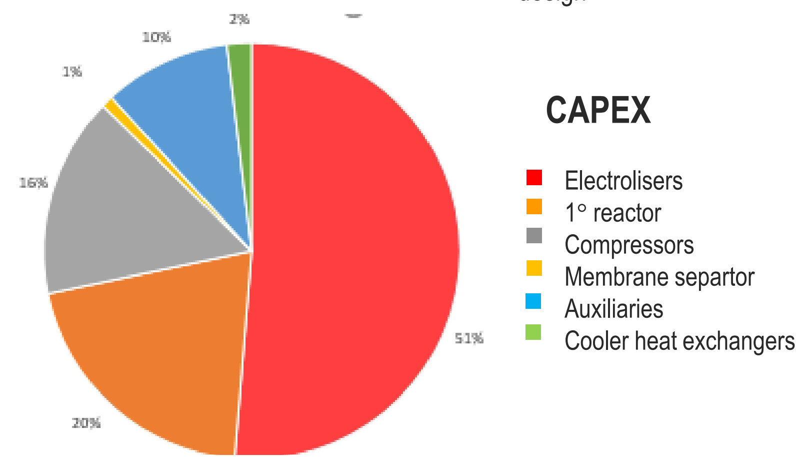
Second configuration:

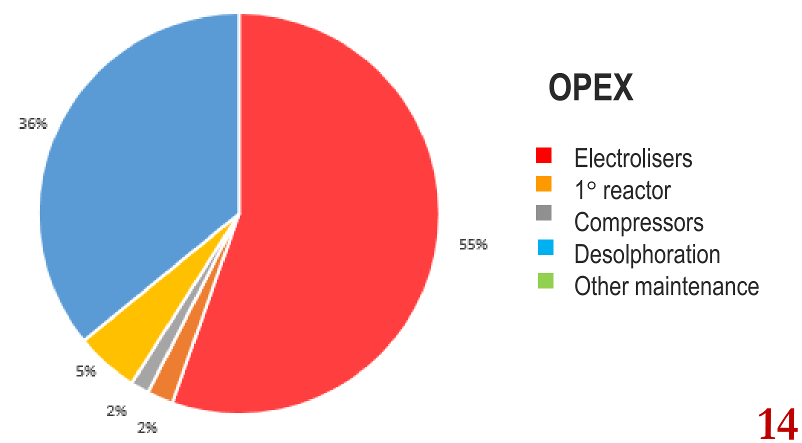
Efficiency: up to 56%

CAPEX: 4,34 M€ for 200 Nm3/h → 21,7 k€ / $(Nm^3/h)_{design}$

OPEX: 870 k€/year. → 4,4 k€ / $(Nm^3/h)_{design}$





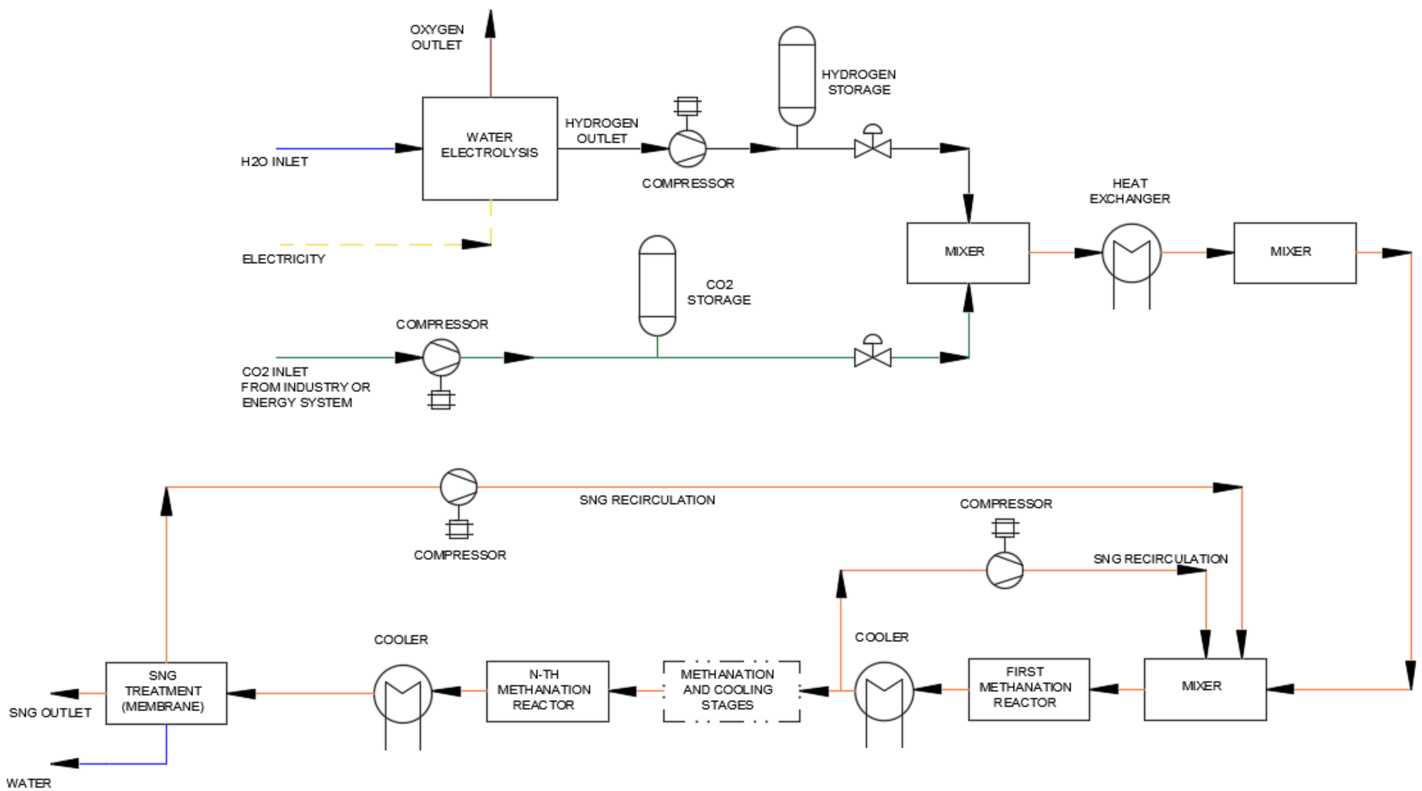


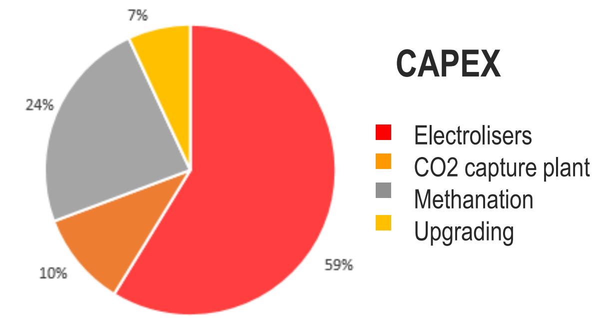
Possible P2G configurations for Italian framework

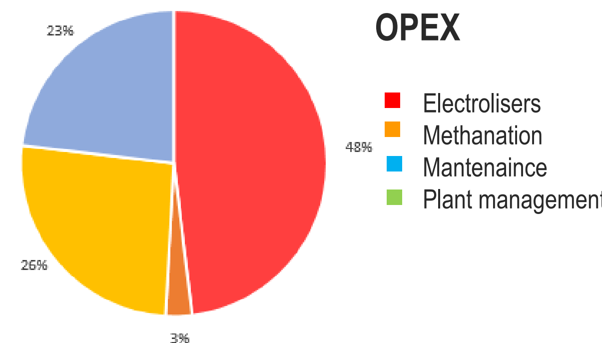
Second solution: Power to Methane (P2M)

Third configuration (no biogas available):

Efficiency: up to 56%
CAPEX: 290 M€ for 4400 Nm3/h ⟶ 65,9 k€ / $(Nm^3/h)_{design}$
OPEX: 38 M€/year. ⟶ 8,6 k€ / $(Nm^3/h)_{design}$







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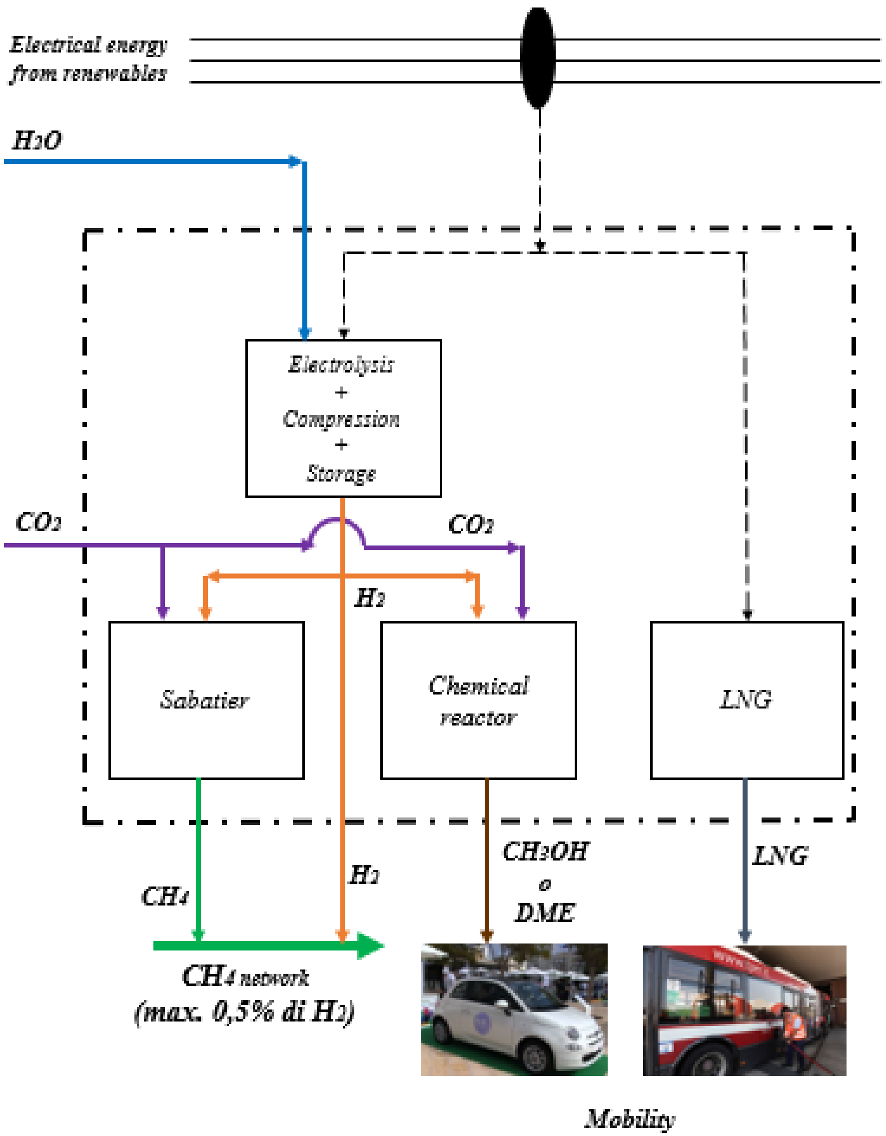

THE E-CO2 PROJECT

Regional founded project

Aims of the project:

- To provide an estimation, on a regional scale, of the potential production of CO_2 to be used for syngas production
- **To experimentally characterize all the involved devices in the P2G chains**
- To technically and economically demonstrate the potential use of synthetic fuels
- To identify models able to simulate all the involved technologies and processes based on experimental data

Duration: 2019 – 2020 (24 months)

Total funding: 768 k€ (from Emilia Romagna region)

Involved partners: **CIRI FRAME (UNIBO)**, CIDEA, LEAP, ENEA, 4 industrial partners are also involved: a cement plant operator, a gas DSO, a bus company, an equipment producer

Future developments and conclusions

THE SUPERP2G PROJECT

European founded project

The project is financed through the ERA-Net SES 2018 joint call (RegSys = Regional Energy Systems) to develop solutions that make it possible to efficiently provide, host and utilize high shares of renewables, up to and beyond 100% in the local or regional supply by 2030

Aims of the project:
To provide a set of tools and procedures to foster the implementation of P2G in the planning as well as in operation of P2G in integrated energy systems as a function of size, performance, local H_2 demand, infrastructure.

Duration: 2019 – 2022 (36 months)

Total funding: 2,5 M€

Involved partners: DTU ME, DTU Elektro, GreenLab Skive, JKU Linz, DBI-GTI, DVGW-EBI, CNR, **UNIBO**, RUG-FEB and several interested stakeholders such as ERIG (European Research Institute for Gas and Energy Innovation)

Future developments and conclusions

To conclude:

- **P2G implementation would ensure several benefits to the Italian energy sector** in which electrical energy production from renewable and unpredictable plants is expected to rapidly growth.

- 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 CO2 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 CO2 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, **several barriers at production and customers' side still hinder the complete market uptake**. In addition, no environmental benefits would be possible in terms of CO2 emissions reduction as occurred in P2M plants.

- The consequence is that **incentives are fundamental to encourage P2G investments**. Particularly, rewarding policies, like carbon tax or feed-in tariff are required to increase the economic sustainability.

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