**POLITECNICO DI MILANO**
Energy and Emissions in Transportation Systems
Prof. Guandalini

Project Work

# Truck fleet conversion: from Diesel to Hydrogen

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# 1. SUMMARY

The goal of the project is the evaluation of the introduction of hydrogen as an energy carrier for a heavy-duty vehicles fleet, currently powered by Diesel fuel.
The technologies investigated for hydrogen production are water electrolysis (both PEM and alkaline) and methane steam reforming (both with and without carbon dioxide capture system).
For each technology involved, the main characteristics will be presented and then the following aspects will be analyzed and compared:

- Technical aspect;
- Economic aspect;
- Environmental aspect.

The final step of the study is the comparison between the current Diesel situation and the hydrogen solution proposal; thus, a comparison between the vehicle consumption and range, the emissions associated to the WTW analysis and the fuel costs for a truck will be presented as a result.

# 2. INTRODUCTION

## 2.1. MAIN CHARACTERISTICS OF HYDROGEN AS ENERGY CARRIER AND PRODUCTION TECHNOLOGIES OVERVIEW

Hydrogen is the lightest and plentiful chemical element of the universe; it is composed of a stable molecule that makes hydrogen particularly suitable for long term energy storage.

Hydrogen is characterized by a high energy content on mass basis (120 MJ/kg) but since its density is low, the energy per unit of volume is much lower with respect to other conventional fuels in same conditions.
Hydrogen does not exist in nature as a pure single molecule, but it should be extracted from other compounds, such as water or hydrocarbons.

The production processes are very energy intensive and can be listed in:

- Steam reforming or partial oxidation of hydrocarbons;
- Gasification or pyrolysis of solid fuels such as coal and biomass;
- Water electrolysis.

Moreover, hydrogen production can be classified into three different categories: grey, blue and green hydrogen, depending on the primary sources used and the associated emissions.

Green hydrogen is the only variety produced in a climate-neutral manner, while grey hydrogen is the most common form, generated from natural gas or methane through the steam reforming. In addition, blue hydrogen uses the carbon generated from steam reforming, then captured and stored on the ground. This kind of process reduces the carbon emissions since 80-90% of the generated carbon can be grabbed.
Green hydrogen is mainly produced by using clean energy from surplus renewable energy sources, such as solar or wind power, through a process called electrolysis. Nevertheless, hydrogen production can be classified as green even if the input electricity production is not from renewable sources. However, steam reforming, gasification and pyrolysis are available not only for fossil fuels, since the production can start from biomass or residuals from agricultural processes, too. In this case, these systems can be labelled as blue.

Hydrogen is commonly used in industries since it is a basis reactant for chemical processes and for oil refinery. Today the worldwide production is around 600 billion $Nm^3$ per year, almost 95% from fossil sources: 50% is from natural gas through steam reforming, which represents the cheapest technology, 30% from hydrocarbons cracking and the remaining 15% from coal gasification. Nowadays, water electrolysis represents only 1-2% of the $H_2$ production with respect to the other methodologies.

## 2.2. STATE OF THE ART

### 2.2.1. TECHNOLOGIES FOR HYDROGEN PRODUCTION

As previously discussed, hydrogen production can be performed through three main methods:

- Steam reforming or partial oxidation;
- Gasification or pyrolysis of solid fuels;
- Water electrolysis.

#### Steam reforming

At the state of the art, steam reforming is the most common solution and well developed. It is characterized by a high efficiency (70-80%) and it is cost effective, since the production costs are estimated around 1.5/2 € per kilogram of $H_2$: therefore, it is adopted by large plants for economy of scale. The process is driven by two main chemical reactions:

$$CH_4 + H_20 \leftrightarrow CO + 3H_2$$

$$CO + H_20 \leftrightarrow CO_2 + H_2$$

The first reaction is strongly endothermic, so heat is provided by external combustion or by reactants partial oxidation, injecting $O_2$. Since the vaporization of methane produces carbon monoxide $CO$, the second reaction is induced in order to avoid $CO$ emissions thanks to an excess of water at inlet. The chemistry is favoured by high temperature, above 900°C and low pressure. The actual reactors operate at 20-30 bars in order to pressurize the hydrogen and reduce its volume. However, $CO_2$ emissions per energy content of the product is higher than the direct combustion of methane because of the conversion efficiency. The steam reforming unit includes the presence of a sulphur removal, a hydrogenator and the fired tubular reformer, that is 15-20 metres tall. In addition, the system also contains a heat recovery component.

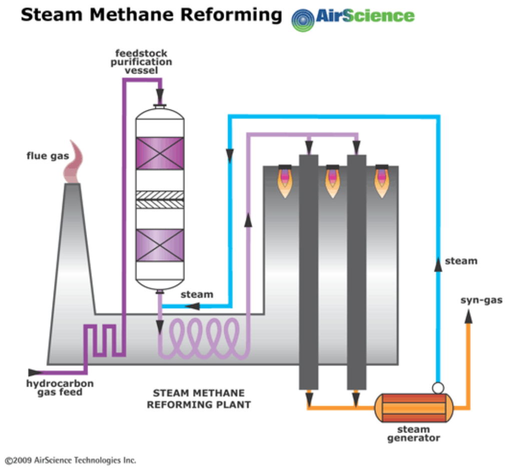



*Figure 1 - Steam Reforming Plant*

The second methodology is represented by both gasification and pyrolysis. Gasification implies the reaction of a fuel with oxygen and water in an adiabatic reactor. Since at high temperatures the fuel components, such as $H$, $C$ and $O$, are volatile, the reaction converts them into $CO$, $CO_2$ and $H_2$. The final products composition is settled by adjusting the $O/C$ and $H_2O/C$ ratios. Its efficiency is around 60-80% but $CO_2$ emissions must be regulated. Pyrolysis is based on the same principle, since it involves a thermal decomposition without oxygen that produces solid char, a liquid pyrolysis, and a syngas. The operational temperatures are between 400-800°C.

Moreover, steam reforming production systems could include the carbon capture system, that allows to reduce the emissions.
However, $CO_2$ generated by the process is low-pressure and rather difficult to recover, with a capture rate between 60 and 90%. The captured carbon dioxide can be stored in CCS (Carbon Capture and Storage) systems or reused in CCU (Carbon Capture and Utilization) systems. The additional advantage of CCU is that it transforms carbon dioxide into a 'raw material' that can be incorporated into virtuous circular economy processes. In addition, all these processes can be integrated into the production of electricity from renewable sources.

Focusing exclusively on CCS systems, the other important aspect, apart from the capture rate, concerns the storage of captured $CO_2$. The best way to do this is to use natural resources, i.e., the 'spaces' that already exist in nature to store it, such as those provided by depleted natural gas or oil fields. In other words, former natural reservoirs that have been emptied of their contents over the years are being filled with carbon dioxide. The capacity for geological storage of carbon dioxide in depleted natural gas fields and saline aquifers is not easy to the quantified, but it is nevertheless important. In other words, carbon dioxide is filled into former natural reservoirs that have been emptied of their contents over the years.

The main difficulty facing any method of capturing and reusing $CO_2$ is that the carbon dioxide molecule is the most stable of all carbon compounds, so separating it from other gases, breaking down its bonds or binding it to any other substance always requires a lot of energy. There are different solutions for overcoming this thermodynamic constraint, such as the use of ionic liquids: a proprietary technology that allows $CO_2$ to be intercepted, but with lower emissions and energy consumption than conventional methods based on amines. High-efficiency electrochemical capture systems are also being perfected, as well as the chemical reduction of $CO_2$ to methanol using hydrogen produced by electrolysis of water using renewable electricity: the methanol produced in this way can be reused to produce energy or used directly as a component of automotive fuel, thus reducing the carbon footprint of the entire process.

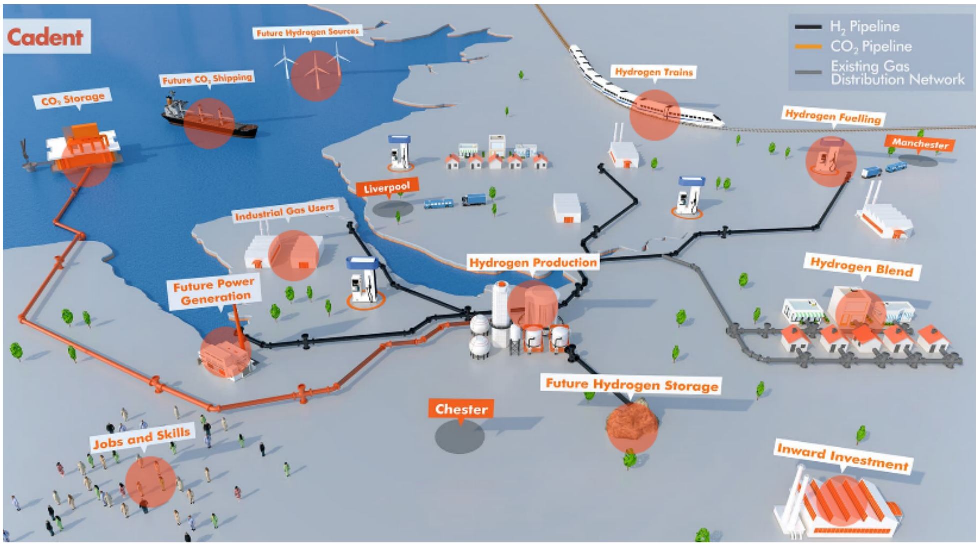



*Figure 2 - Steam Reforming Plant with CCS*

## Electrolysis

Electrolysis of water is an alternative process for hydrogen production, where the primary source is water that is split into hydrogen and oxygen in an electrochemical cell. Since the temperature strongly affects the reaction, two solutions are available:

- Low temperature cells (alkaline and PEM);
- High temperature cells (SOEC).

While the formers are commercially available on markets, the latter are still under development.
The contribution of electricity and heat in the process significantly changes depending on the temperature while it remains stable with the pressure, according to the charts below.

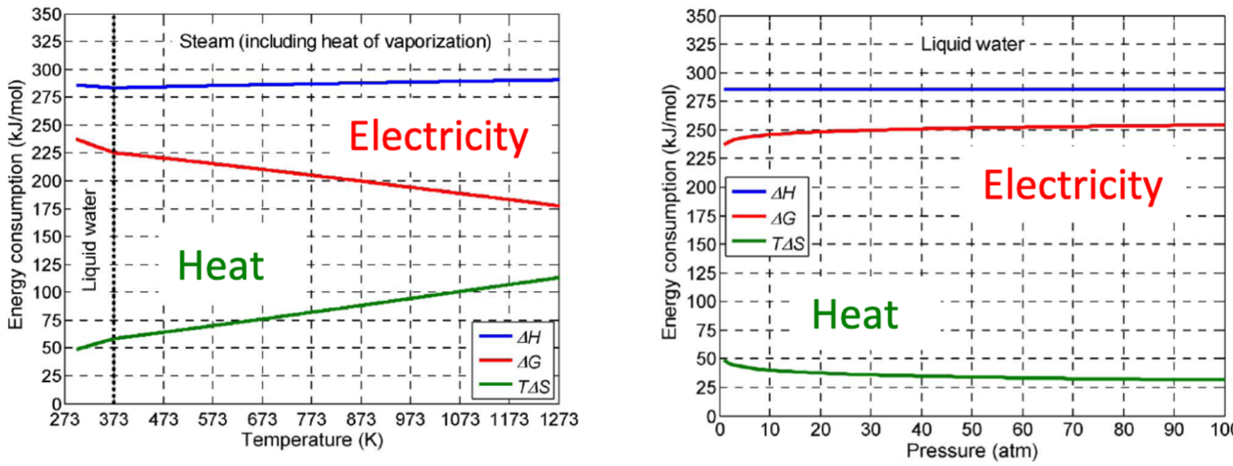



*Figure 3 - Temperature and Pressure effects*

As the first graph points out, the contribution of electricity decreases with the temperature, while heat increases. Thus, the goal is to find a way to work at high temperatures, since the electricity represents the actual cost for the production. The current pressure is about 30 bars, but industries are pushing towards a high-pressure production, in order to save money in the compression step. The hydrogen must be pressurized for the transportation process because of its low density, indeed. Nowadays, the low temperature technologies function up to 100°C, while the high temperature ones over 700°C.

The available technologies for low-temperature hydrogen production are two:

- Alkaline electrolysis.
- PEM.

In both cases, the system is composed of two electrodes and an electrolyte, a material that promotes the flow of electrons and protons. The difference between these two solutions is that in the alkaline case $\mathrm{OH}^-$ electrons move from the cathode to the anode, vice versa in the PEM case $H^+$ protons move from the anode to the cathode. Moreover, different kinds of electrolyte are suitable for the alkaline and PEM solution.
In the first case the electrolyte is an alkaline liquid solution ($KOH$, $NaOH$) and a polymeric splitter is needed in the middle. Hydrogen is a very flammable molecule and, since during the reaction oxygen bubbles are generated, the splitter avoids the eventual explosion that would damage the cell.

In the second solution, the electrolyte is a solid material that avoids the production of bubbles. In this way the process can get hydrogen characterized by higher purity and a more compact system can be obtained. In addition, it allows to increase the current and the productivity of the system.

Alkaline technology has been used in really large plants, such as chemical industries and refineries, during the last years. It is reliable and well-known with respect to the PEM solution. It is sufficiently safe since the only element to pay attention to is the caustic soda electrolyte. From this process, a grade 3 hydrogen (99,9% of purity) can be obtained. However, this value is not enough for transport applications where grade 5 or 6 is required. Therefore, it is necessary to remove pollutants that permeated the membrane, such as oxygen, and the residual fraction of water.

PEM technology is more recent, but the main drawback is the cost: the electrolyte must be made of platinum, which is really expensive. However, this technology is much more efficient and compact. Moreover, hydrogen purity is higher because the solid membrane reduces the permeation. Nevertheless, a purification system is still required for mobility applications.

In conclusion, the state of the art is represented by the graph below. Alkaline electrolysis works at a current density between 0.5-1 A/cm$^2$ with an efficiency between 60-70%. PEM electrolysis allows to operate with higher current density (1-2 A/cm$^2$) and higher efficiency (65-75%). Thus, PEM cells imply lower capital costs since higher current density means smaller systems. Nevertheless, alkaline cells grant higher operational costs.

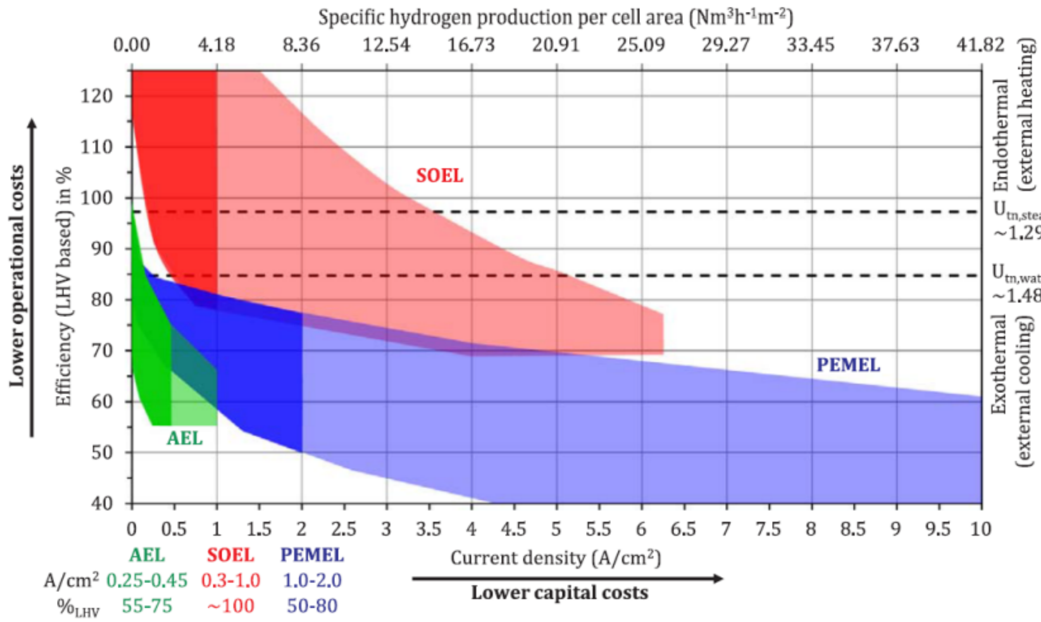



*Figure 4 - Operational - Capital Costs*

## 2.2.2. STORAGE AND SUPPLY

Hydrogen can be transported and stored in three main ways.

The first one is in the form of chemicals (material based) where hydrogen is bound in a stable but reversible way. In this case the hydrogen can be stored using three different materials; those that use adsorption to store

hydrogen on the surface of the material like *MOF-5*, the ones that use adsorption to store hydrogen inside the material. The third way is represented by hydride storage, which uses a combination of solid and liquid materials.

Hydrogen can also be stored as a liquid (physical-based) at low temperature and at atmospheric pressure (storage of cryogenic liquids). The storage of liquid hydrogen requires cryogenic temperatures to prevent boiling conditions, which occur at around -252.8°C.

The main issue is due to the difference in energy density between liquid and gaseous hydrogen. Fluid hydrogen has higher energy density; thus, reaching the required temperature is more energy expensive. In addition, storage tanks and facilities for storing cryogenic liquid hydrogen must be insulated to prevent evaporation in the case that heat warms up the liquid hydrogen due to conduction, convection, or radiation.

Typically, metallic double-walled vessels are used, like *Dewar* container. This is a glass, metal, or plastic container with a cavity; the region between the external and internal walls is under vacuum, which cannot conduct heat by conduction or convection, but only by radiation. Thus, radiation losses can be minimized by applying a reflective coating to the surfaces.

The last storage form is like a high-pressure gas (physical-based). In these cases, storage requires the usage of high-pressure tanks. The current standard for compressed hydrogen storage is 200 bars for industrial applications, from 350 to 700 bars for transport applications.

Four types of vessels, classified according to the used materials, are available for hydrogen storage:

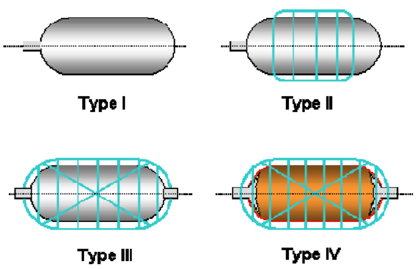



*Figure 5 - Vessel Types*

- Type I: pressure vessel made of metal.
- Type II: pressure vessel made of a thick metallic liner hoop wrapped with a fiber-resin composite.
- Type III: pressure vessel made of a metallic liner fully-wrapped with a fiber-resin composite.

- Type IX: pressure vessel made of polymeric liner fully-wrapped with a fiber-resin composite. The port is metallic and integrated in the structure.

Heavy-duty vehicles commonly use type IV tanks with a storage density around 6 weight%. For a 35 kg of $H_2$ stored, 7 tanks are connected.

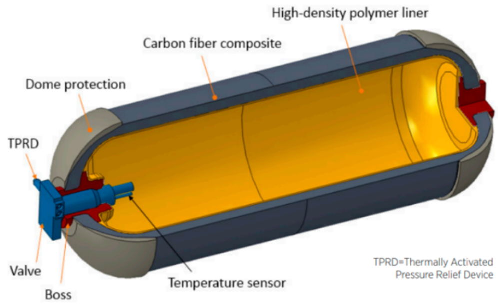



*Figure 6 - Hydrogen Tank*

A vehicle's hydrogen tank must not heat up above 85°C even during fast refueling, but hydrogen is compressed during refueling inducing temperature increasing. Pre-cooling, typically at -40°C is required to stay within the limits (overpressure/overheating) of the vehicle's fuel storage system.

At the state of the art, there are only around 300 refiling stations in the world, and in Italy there is a hydrogen highway project, where 7 stations in 650 km (Bolzano, Trento, Verona, Carpi, Innsbruck, Monaco) are planned to be completed in the next few years.

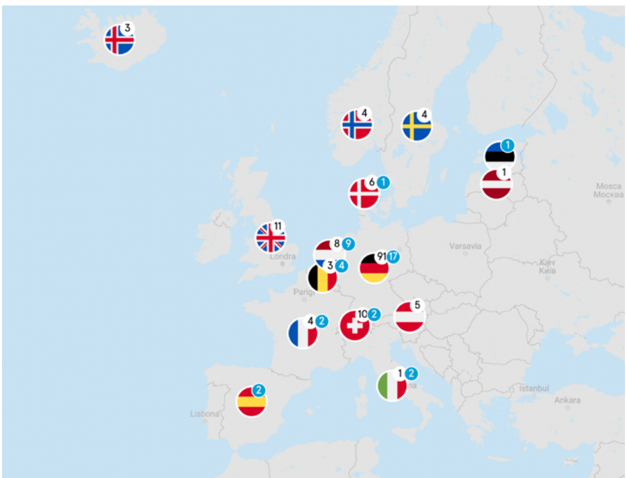


*Figure 7 - Refilling Stations in Europe*

131 20 In operation 40 in progress

### 2.2.3. HYDROGEN STRATEGY and POLICY FRAMEWORK

The EU commission has recently introduced the European strategy for hydrogen, in which the renewable hydrogen is previewed in the long term (green hydrogen produced by electrolysis or by reforming biogas if it complies with sustainability requirements) and low-carbon hydrogen (also called blue hydrogen, obtained by reforming natural gas and combined with CCS, waste or other low-emission technologies) in the transition phase. Grey hydrogen, on the other hand, is completely excluded from fossil fuels without CCS and with a significant emissive impact, which currently accounts for most of the hydrogen produced.

The new European Hydrogen Strategy, "*A hydrogen strategy for a climate-neutral Europe*", defines a common European path to stimulate the use of hydrogen, in view of the objectives of the *European Green Deal* and the long-term decarbonization target of 2050. The role of hydrogen is constantly growing, especially in certain industrial sectors, in transport (mainly heavy and long-haul) as it can contribute to the decarbonization of sectors for which electrification is not an efficient solution. In other sectors, such as residential and commercial building heating, the use of hydrogen is related to the development of "*Hydrogen Valleys*", at least until 2030.

However, the two main challenges remain the still high production costs and rather low demand.

The European strategy sets out a three-stage road map along which a gradual development path for hydrogen can be established.

- In a first phase (2020-2024) the EU should decarbonize the current hydrogen production, with at least 1 million tons of renewable hydrogen and the installation of at least 6 GW of electrolyzers. At this stage, the production, even of large dimensions (up to 100 MW), should be increased. The electrolyzers could be installed alongside existing demand centers, such as large refineries or steel and chemical plants, and ideally connected to local sources of renewable electricity. Infrastructures for the capture and use of $CO_2$ will also be needed to facilitate certain forms of low-carbon hydrogen. This phase would be facilitated by an appropriate regulatory framework, especially with regard to state aid.

- During the second phase (2025-2030) green hydrogen is expected to become a substantial part of the European energy system, with a minimum of 10 million tons of renewable hydrogen by 2030 and 40 GW of installed electrolyzers, to which an additional 40 GW installed outside the European Union will be added. At this stage, hydrogen could already have a sufficient market to develop industrial demand, such as steel, to expand its use in heavy transport and balance renewable-based electricity systems, including the development of autonomous regional clusters and ecosystems (cd. *Hydrogen Valleys*). Investments in electrolyzers in 2030 would reach EUR 24-42 billion. The gas infrastructure should be partly used to provide hydrogen over long distances and to develop appropriate storage facilities. In the same period, EUR 220-340 billion would be needed to directly increase and connect 80-120 GW of solar and wind power
  -

production capacity to provide the electricity needed for electrolysis plants. Investments in the adaptation of half of existing installations with carbon capture and storage (CCS) are estimated at around EUR 11 billion. Investments of EUR 65 billion will also be needed for the transport, distribution and storage of hydrogen and hydrogen filling stations.

- At last, in the third phase (2030-2050) green hydrogen technologies should be sufficiently mature for large-scale development, making a substantial contribution to EU decarbonization by 2050. At this stage the production of electricity from renewable sources is expected to increase substantially, as by 2050 about a quarter could be used to produce renewable hydrogen. Cumulative investments in renewable hydrogen in Europe could reach EUR 180-470 billion by 2050, while those for low-carbon hydrogen could reach EUR 3-18 billion.

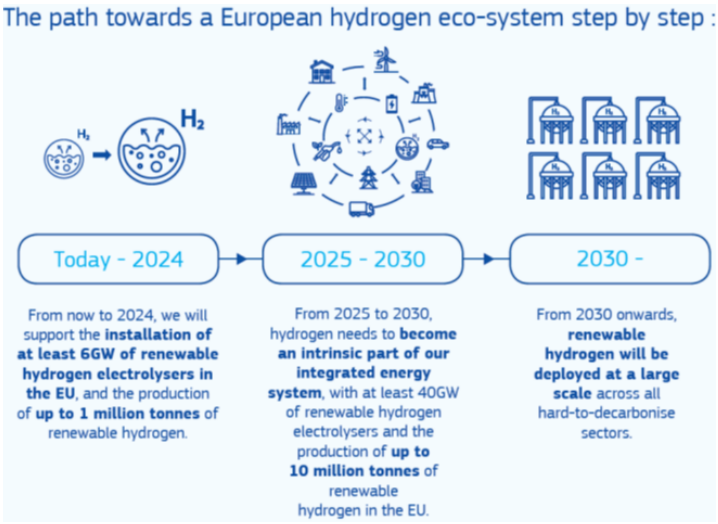



*Figure 8 - European Plan*

The increase in hydrogen demand and supply is likely to require various forms of support, differentiated in line with the vision of this strategy to priorities the deployment of renewable hydrogen. During a transition phase, adequate support will be needed for low-carbon hydrogen, the so-called blue hydrogen.

In Italy, hydrogen will be able to play a fundamental role both in absolute and indirect form. The first concerns the direct use in the industrial sectors of chemistry and refining as a raw material or in the energy-intensive industry that requires heating at very high temperatures (including over 1,000°C), and/or reducing agent in steelworks, and as a fuel in mobility (primarily heavy long-range). The second will be used especially in a second stage where it will be more abundant and cheaper, to produce electricity and heat through the injection of hydrogen into the gas network mixed with natural gas or pure (100% $H_2$), developing liquid fuels with low or zero carbon emissions (low carbon liquid fuels).

The produced hydrogen, hydrogenated fuel, and synthetic fuel will be able to contribute to the relaunch of the automotive sector after the health emergency. Hydrogen is a high energy density storage medium and can also play a role in integrating renewable sources into energy systems: it is suitable for large-scale storage, since thousands of tons of hydrogen can be stored for a storage capacity of hundreds of GWh, and for long periods, up to seasonal accumulations; thus, it is a solution that allows to connect energy networks (sector coupling) and to transfer excess production from renewable energies to other sectors.

To date, hydrogen consumption in Italy is almost entirely limited to industrial uses in refining and chemistry (ammonia) and is predominantly grey. Hence, these companies can promote the replacement of grey hydrogen with environmentally sustainable hydrogen. The current production typically takes place on site in large steam reforming plants of natural gas and directly feeds chemical processes. The final consumption of hydrogen in Italy is about 16 TWh, equal to 1% of final energy consumption at national level (1,436 TWh) and corresponding to about 480,000 tons per year, of which about 8,500 tons per year are marketed in cylinders and special pipes.

Italy can apply as an enabler of the European strategy on hydrogen for the following three key features:

- The presence of a widespread network for the transport and distribution of gas and the strategic geopolitical position in the Mediterranean. Through a series of targeted interventions, the country can be the basis to accommodate ever-increasing percentages of hydrogen for internal use and, potentially in the long term, for export to northern Europe.

- It is the second country in Europe for added value of the manufacturing sector and it is the first in number of small and medium-sized manufacturing enterprises, an economic fabric industrial which includes some of the distinctive skills in the production of technologies applied along the supply chain, such as thermal technologies potentially applicable to hydrogen, where Italy turns out to be the first producer in Europe, or certain sectors of mechanical technologies for the management of pressurized gases. Although there are areas of technology and production where it is still necessary to strengthen its positioning, Italy can also count on the large national players in research and energy able to act as leaders in large processes of innovation and technology transfer.

- Italy can exploit its capacity to integrate hydrogen into the energy system, thanks to its distinctive characteristics. The readiness of the country to use gas and the availability of dedicated infrastructure that results from it, can act as a facilitator for the transition to hydrogen in the country. Moreover, as regards the production of green hydrogen, Italy can count not only on a positioning that places it among the most virtuous countries in Europe for the share of renewables in electricity production

(17.8%) but also on high expertise in the production of biogas and biomethane (fourth world's producer of biogas and second in Europe).

Given the specificities of the country system, alternative production routes should obviously not be excluded, such as the production of hydrogen from municipal solid waste, non-recyclable plastics (*Plasmix8*) and CSS, from bioenergy (biomass, biogas, etc.) and with chlorine-soda electrolyzers. These are not mentioned explicitly

in the official European documents but can produce clean and renewable hydrogen when powered by renewable energy at competitive prices and represent a share of current Italian production. The technology of hydrogen production from waste, with a view to a circular economy, contributes to the hydrogen exploitation of waste such as *Plasmix* and CSS, facilitating the current process of management of such waste, the production of which is expected to increase in the coming decades. A further contribution to low-emission hydrogen production can come from industrial hydrogen production plants (steam reformers) through the replacement of traditional natural gas with biomethane produced from waste, agrozootechnical waste and

from water and sludge treatment. Moreover, hydrogen produced by bioenergy could be a component that is added to all uses when mixed in the natural gas network. The combination of these technologies is a bridging solution, which could contribute to the generation of increasing volumes of $H_2$, such as to stimulate demand and investment in infrastructure, and accompany the progressive spread of green hydrogen, with the reduction of production costs. Regarding $CO_2$ numbering operations, it is underlined the need to carry out a feasibility analysis with a particular focus on safety aspects in relation to the storage systems available to enable their development.

A national hydrogen strategy aiming for real success should also be based on an analysis of the country's current infrastructure situation, to make appropriate use of it and minimize the economic and social impact of the transformations needed to pursue the objectives of full decarbonization by 2050 and beyond.

In this perspective, it is necessary to keep in mind, among other things:

a) The capillarity of the Italian natural gas distribution networks in physical terms and their ability to "make system" with the remaining part of the natural gas infrastructure supply chain in ensuring peak capacity and energy storage capacity against peak demand.

b) The compatibility of these networks with hydrogen, with up to 20% blending with natural gas, which is currently being tested at European and national level.

c) The current level of penetration of gas among Italian households, equal to about 92%, and among small craft and service activities, which altogether "weigh" for more than a third of the current consumption of natural gas.

d) The high level of traceability of the electricity generated by FER plants, enabling certification of the use of green hydrogen in industrial sites and an immediate decarbonization effect on the so-called hard-to-abate sectors.

### 2.2.4. MOBILITY APPLICATIONS

Because of the possibility of sector coupling, hydrogen is an energy hub that has been emerging in recent years. Hydrogen deployment would involve several sectors, with the aim of bringing positive effects in terms of energy, costs and emissions:

- Mobility: the aim is to bring both local and global emissions to zero and the development of integrated systems with fuel cell electric vehicles (FCEVs).
- Industry: with the main focus on all "hard-to-decarbonise" activities.
- Energy storage: the possibility of storing energy on a large scale.

The introduction of hydrogen in the mobility sector has been touched upon several times in history, but never on a large scale. Although the first real hydrogen fuel cell car on sale was the *Hyundai Tucson FCEV* in 2013, the first hydrogen concept dates back much further.
As early as 1807, inventor Francois Isaac de Rivaz designed the first four-wheeled prototype powered by hydrogen and oxygen gas.
About fifty years later, in 1860, the 3-wheeler *Hippomobile* was designed with a 2-stroke hydrogen cylinder created for the car by electrolysis of water and the gas directed to the horizontal engine.
In 1933, the first truck was designed by the electric company *Norsk Hydro*, while in 1959 the first hydrogen-powered farm tractor the first example of the application of fuel cells for the traction.
However, seven years later, a real revolution came with the first passenger *FCV: General Motors Electrovan*.

*Figure 9 - General Motors Electrovan*

Despite its bodywork, *Electrovan* was a vehicle with very little load capacity, with the rear deck completely occupied by the hydrogen and oxygen tanks as well as the fuel cell system, consisting of 32 modules. The cells were able to provide 32 kW of continuous power with peaks of up to 160 kW, enabling the van to sprint to 100 kmph in 30 seconds and to reach a top speed of 70 miles (112 kmph), with a range of 200/240 kilometres.

At the time, this was an incredibly advanced technology, but it had its drawbacks in terms of cost because the cells at the time were made of platinum, and weight, since the vehicle weighed around 3,200 kg, which forced *General Motors* to abandon the project and scrap the prototype shortly after it was unveiled to the public as a concept. The project remained a concept, but it was a direct precursor of the hydrogen cars currently on the market.

Hydrogen has also been seen as a potential energy carrier for rail transport for some years now. Since 2018, *Alstom* has been putting into circulation passenger trains in Germany that run entirely on hydrogen. Hydrogen-powered trains are an ideal solution for reducing emissions as they could replace Diesel-powered trains running on non-electrified sections of the rail network.

*Figure 10 - Coradia iLint Hydrogen Train*

In the field of heavy transport, the idea of using hydrogen as an energy carrier has only become widespread in the last years. As with cars, one manufacturer that believes strongly in hydrogen as an alternative energy source is *Hyundai*. They with the long-term *FCEV Vision 2030* programme presented in 2018, affirmed the desire to pursue fuel cell technology not only for passenger cars but also for commercial vehicles.

The *Hyundai Xcient Fuel Cell* belongs to the latter category. It follows on from the *HDC-6 Neptune* prototype, shown at the *North American Commercial Vehicle Show* in Atlanta in 2019. In this case, it is not a prototype, but a model that has already been put on the roads of Switzerland thanks to *Hyundai Hydrogen Mobility* (the joint venture between *Hyundai* and the *Swiss company H2 Energy*) receiving very positive opinions.


*Figure 11 - Hyundai Xcient Fuel Cell*

The introduction of hydrogen in heavy-duty transport is being followed very closely because they are currently one of the main sources of pollution in the transport sector, responsible for 5-10% of $CO_2$ global emissions.

From a technological point of view, the introduction of hydrogen in mobility goes on with the development of fuel cell technology. This is a form of power supply that uses fuel cells, placed on board the vehicle, to generate electricity through the chemical energy provided by the hydrogen itself.

The operating principle of the engines that power the hydrogen trucks is like that of a battery, but the difference is that the battery stores energy, while the fuel cell converts the chemical energy in a tank through an electrochemical process. In this case, the hydrogen contained in a special tank passes through the combustion cell where it separates from the electrons, supplying electrical energy to the electric motor.

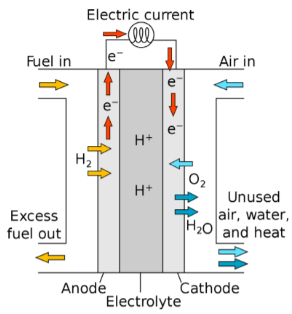



*Figure 12 - Fuel Cell Functioning*

There are different types of fuel cells:

- Low temperature:
    - Alkaline (Alkaline Fuel Cell, AFC);
    - Polymer Electrolyte Membrane Fuel Cell (PEM or PEFC);

- Phosphoric Acid Fuel Cell (PAFC).

- High temperature:

  - Molten Carbonate Fuel Cell (MCFC);

  - Solid Oxide Fuel Cell (SOFC).

| Name | Electrolyte | Ion Transported | Operating Temperature |
|---|---|---|---|
| AFC | Alkaline (liquid) | $OH^-$ | 70-250 °C |
| PEFC or PEM | Polymeric (solid) | $H^+$ | 80-120 °C |
| PAFC | Phosphoric Acid (liquid) | $H^+$ | 200 °C |
| MCFC | Molten Carbonate (liquid) | $CO3^{--}$ | 600-700 °C |
| SOFC | Metallic / Ceramic Oxide (solid) | $O^{--}$ | 650-1000 °C |

*Table 1 - Fuel Cells*

The engine of a hydrogen-powered truck is therefore an electric motor: it draws energy both from the combustion cells and from the batteries installed on board the vehicle. When the vehicle does not require energy from the combustion cells, it recharges the batteries, increasing the truck's range. The range of hydrogen trucks varies from 400 to 600 km, depending on the capacity of both the tanks and batteries.

The advantages of a hydrogen-powered heavy-duty vehicle are:

- Environmental sustainability: the chemical reaction of a combustion battery produces only water as a result. This means that the pollutant emissions that characterise other types of engines, such as the Diesel engine, are reduced to zero.

- Refuelling times: unlike an electric truck, which takes hours to recharge the batteries, a hydrogen truck only takes a few minutes to refuel completely.

- Range: The combination of a fuel cell and a battery pack increases the range of the truck considerably compared to a truck with just batteries.

The disadvantages, on the other hand, are mostly related to high costs and the need for an AC/DC converter, fuel pre-processing and materials thermo-mechanical compatibility.

## 2.3. EXAMPLES OF PROJECTS

Some examples of hydrogen applications in the mobility industry are discussed below.

## 2.3.1. ALSTOM CORADIA

*Coradia* is the trade name that distinguishes a family of trains produced by *Alstom*. *Coradia iLint* is the first hydrogen-powered (fuel cell) passenger train. Developed starting from *Lint 54*, it is 54 meters long, composed of two car bodies, has a weight of about 120 tons distributed on 4 2-axle trolleys, a capacity of maximum 300 passengers, an autonomy of about 800-1000 km and can reach a cruising speed of 140 kmph. The *iLint* is a one-of-a kind train, being the first ever hydrogen train to enter commercial service. From just a prototype, now the *iLint* rolls along some intercity-regional lines in Germany and is set to be operative in other connections in other countries. In Italy, for example the project "*H2iseO*", powered by *ENEL* and *FNM*, aims at revamping and improving the Brescia-Iseo railway line, by replacing the current and dated Diesel train fleet, with a total of 14 environmentally sustainable *Coradia iLint* trains (together with 40 hydrogen busses).

The train runs by powering its electric engine via the electricity produced by the chemical reaction between oxygen and hydrogen, which is safely stored under pressure in the fuel cells. This mechanism produces only water vapor and heat, centralizing emissions along the process of hydrogen production, that can be powered by both renewable energy and fossil fuel.

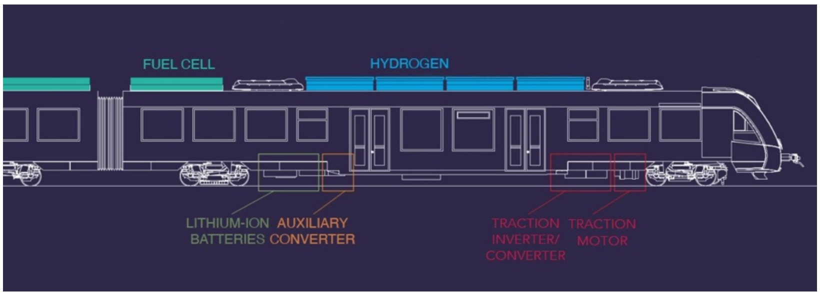



*Figure 13 - Alstom Coradia iLint*

## 2.3.2. HyCARE PROJECT

The *EU-funded HyCARE* project is developing a new method for storing hydrogen in the solid state, using metal hydrides, and using energy storage in the form of heat thanks to phase change materials. The tank for the storage of heat and solid-state hydrogen is based on an innovative concept that links hydrogen and heat storage for stationary storage of excess renewable energy.

*HyCARE* targets the following goals:

- High quantity of stored hydrogen ≥ 50 kg;
- Low pressure < 50 bar, low temperature RT to < 100°C;
- Low footprint, comparable to liquid hydrogen storage (≥ 60 kg $H_2/m^3$);
- Hydrogen storage coupled with thermal energy storage;
- Improved energy efficiency;

- Integration with an electrolyzer (EL) and a fuel cell (FC);
- Demonstration in real application;
- Improved safety;
- Techno-economical evaluation, Life Cycle Analysis (LCA);
- Exploitation of possible industrial applications;
- Dissemination of results at various levels;
- Engagement of local people and institution in the demonstration site.


*Figure 14 - HyCARE*

### 2.3.3. H2HAUL

The European Commission's transport has imposed a target of a 60% reduction in $CO_2$ emissions by 2050. For this reason, a drastic reduction in greenhouse gas emissions from freight transport is needed. Since heavy-duty vehicle (HDV) traffic is expected to increase dramatically, EU is funding the *H2Haul* (*Hydrogen Fuel Cell Trucks for Heavy Duty Zero Emissions Logistics*) project, which aims to develop and demonstrate 16 *Iveco* and *VDL*-branded fuel cell trucks to zero emissions in four European countries and to build 6 new $H_2$ refueling

stations near the sites where the vehicles will operate. Directive *2014/94/EU* requires Member States to develop national policy frameworks not only for the development of alternative fuels but also for their infrastructure. As a matter of fact, for hydrogen, the directive aims to ensure a sufficient number of publicly accessible refueling stations in the Member States to be built by the end of 2025. In the *H2Haul* project, 350 and 700 bar stations will be used to refuel the trucks. These stations typically comprise gas storage, compression, and dispensing equipment to refuel vehicles according to internationally agreed protocols.

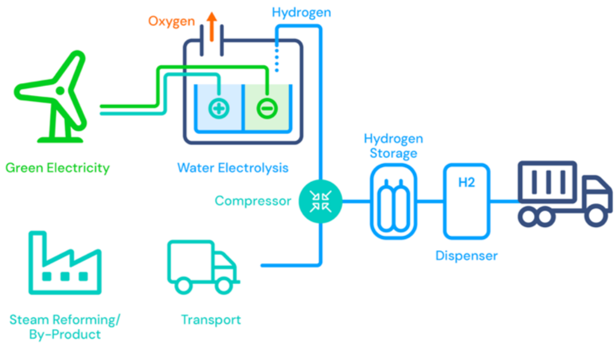



*Figure 15 - H2Haul*

# 3. CASE STUDY DESCRIPTION

The project site is in the industrial area of the city of Brescia. The company that owns the vehicles under study is *Germani Trasporti*. Its headquarter, besides being located near the highway link between A4 and A21, is close to two important production sites:

1) the *Alfa Acciai* steelworks;
2) the *a2a* waste-to-energy plant.


*Figure 16 - Project Overview*

The work that will be presented next focuses on the energy, economic and environmental comparison between two alternatives: the first involves the installation of an electrolyzer in the *a2a* plant, while the second involves the introduction of a reformer into the steelworks.

Given the characteristics of the site, it is assumed that the hydrogen is transported in both cases via a pipeline that reaches the filling station in the *Germani* depot.

The main characteristics of the three sites are briefly presented below.

*Germani Trasporti* is one of the leading companies in the national and international rubber market for the transport of liquid and solid chemicals, hazardous and non-hazardous industrial waste, and the management of activities aimed at the transport of cryogenic gases.
*Germani* has a fleet of about 150 diesel vehicles, classified "*Euro 6*", with an age of less than 3 years. In general, *Germani*'s fleet consists of road tractors, tractors with hydraulic banks, road trains with hydraulic banks and tipping semi-trailers, pallets, silos, stainless steel tanks and ebonite.
For the project considerations, the assumption made is that the fleet is entirely composed of *Hyundai XCIENT* trucks and that 50 vehicles, with a tank of 35 kg, requires a complete refilling every day.

*A2a Waste to Energy Plant* is a plant able to use waste that is not usefully recyclable in order to produce electricity and heat. Undifferentiated waste is discharged into the collection and mixing tank. From there, through overhead cranes, they are loaded into the hoppers that feed the grids on which the combustion takes place. The combustion lines consist of steam generators, with combustion chambers whose temperature is constantly adjusted to over 1,000 Celsius degrees, for complete oxidation of waste. The heat produced by combustion generates high-pressure steam, which is fed into a turbine to produce electricity and, subsequently, used to heat the water that feeds the district heating network of the city.

730,000 tons of waste treated in one year

610 GWh of electricity produced in one year

820 GWh of heat produced in one year

*Alfa Acciai* represents one of the largest electro-steel sites in Italy and it represents a pivot of the circular steel economy giving new life to over a million tons of scrap metal every year. Scrap comes from separate collection, industrial/railway demolitions, end-of-life vehicle treatment plants, from machining and so on. The manufactured steel, ceased their useful life, can be recovered 100% and infinite times through the recasting, without any loss of quality and without any degradation in the mechanical properties so as to be indistinguishable from the material' new. The life cycle of steel is potentially endless, making it a real "permanent resource", essential for the development of a sustainable economy.

The purpose of the analysis to be carried out is to compare two different hydrogen production technologies:

1) Electrolysis of water (PEM and Alkaline);
2) The steam reforming of methane gas (with and without CCS).

In the first mode, hydrogen is produced in *a2a* electrolyzer powered by the electricity generated by the combustion of waste in the waste to energy plant.
In the second mode, hydrogen is produced by burning methane gas in a reformer inside the *AlfaAcciai* steel mill. In this case the heat required for combustion is supplied by cooling tower for secondary processes in the steelworks.

At environmental level, electrolysis and methane reforming have different contributions. Whereas electrolysis has no direct emissions due to the production of hydrogen, steam reforming emits carbon dioxide directly.
As mentioned before, both for environmental and costs assessment, the two reforming solutions will be considered: with and without carbon dioxide capture.

The $CO_2$ generated from SMR can either be either released into the atmosphere in plants without capture systems or captured and stored. These two options define two different types of hydrogen: the first produces grey hydrogen and the second blue hydrogen.
In order to get a more complete view of the emissions associated with hydrogen production, it is necessary to also include in the comparison the pollutant emissions related to the production of energy inputs in the electrolysis and reforming processes.
Emissions related to electricity production refer to those from the waste-to-energy plant, while the value of emissions related to input methane in the reformer is representative of the whole methane chain. Emissions associated with heat have been neglected, since there is not any information about it.

# 4. TECHNICAL EVALUATION

An *Excel* sheet has been developed in order to compare the different solutions. PEM and alkaline electrolysis have been analysed first, then steam reforming production.
The results are showed by energy and electricity consumption, costs and emissions during the whole $H_2$ generation.

## 4.1. ELECTROLYSIS

First of all, the input parameters have been set. The cell is characterized by its specific polarization curve, that defines the cell voltage.

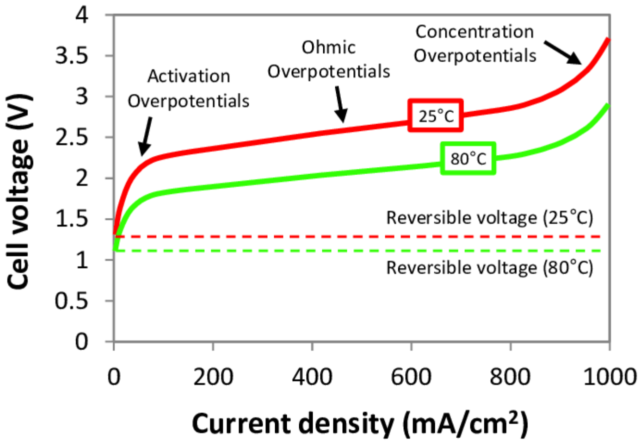



*Figure 17 - Polarization Curve*

The equation that defines the specific polarization curve is:

$$V = 1.7 + 0.11 * i$$

The current intensity $\mathrm{i}$ has been set equal to 1.9 A/cm$^2$, according to the state of the art. The hydrogen production has been settled, equal to $1.75\ \mathrm{kg/min}$, since *Germani* trucks need a complete refilling in 20 minutes. Then, given the number of cells in series $N_S$, set equal to 180, the number of cells in parallel $N_P$ has been computed, equal to 21. The cells in series are divided into two different stacks, due to mechanical constraints.

The calculations have been performed using the formula below:

$$\dot{n}_{H_2} = \frac{i * A * N_c}{2 * F} = \frac{i * A * N_P * N_S}{2 * F}$$

Where $A$ is the area of the cell in cm² and $F$ is the Faradaic Constant, equal to 96,485.3365 C/mol and represents the energy charge of one mole of electrons.
Yet, the stack voltage has been computed as the product between the number of cells in series and the cell voltage and it indicates the voltage of the whole system. Next, the stack power has been calculated as the product of the stack voltage and the current intensity multiplied by the area of the cell. In conclusion, the multiplication of the stack power and the number of cells in parallel gives the nominal power and the ratio between the nominal power times the refilling time and the hydrogen production gives the specific consumption in kWh over kg of hydrogen.

| | |
|---|---|
| Polarization curve [V] | 1.7+0.11*i |
| Faradaic efficiency | 0.98 |
| Area of the cell [cm²] | 400.00 |
| Number of cells | 3,780.00 |
| Number of cells in parallel | 21.00 |
| Number of cells in series | 180.00 |
| Current intensity [A/cm²] | 1.90 |
| Faradaic constant [C/mol] | 96,485.34 |
| H2 molecular weight [kg/kmol] | 2.00 |
| Refilling time [min] | 20.00 |
| H2 required [kg] | 35.00 |
| | |
| Hydrogen production [kg/min] | 1.75 |
| | |
| Mass of H2 [kg/s] | 0.03 |
| Moles of H2 [mol/s] | 14.58 |
| Cell voltage [V] | 1.91 |
| Stack voltage [V] | 343.62 |
| Stack power [kW] | 261.15 |
| Nominal power [kWel] | 5,484.18 |
| Specific consumption [kWhel/kg] | 52.23 |

*Table 2 - PEM Electrolysis*

The same approach has been conducted for the alkaline electrolysis. The main differences are given by the lower current intensity, chosen equal to 0.6 A/cm$^2$, the bigger area of the cell (1200 cm$^2$), and, therefore, the number of cells in series and in parallel, 4200 and 7, respectively. In addition, the faradaic efficiency is lower, 0.9 against 0.98 for the PEM electrolysis. Hence, the cell voltage, 1.766 V, the stack voltage and power are lower. For what concerns the nominal power and the specific consumption, the difference is reduced, since the hydrogen production is the same.

| | |
|---|---|
| Polarization curve [V] | 1.7+0.11*i |
| Faradaic efficiency | 0.90 |
| Area of the cell [cm$^2$] | 1,200.00 |
| Number of cells | 4,200.00 |
| Number of cells in parallel | 7.00 |
| Number of cells in series | 600.00 |
| Current intensity [A/cm$^2$] | 0.60 |
| Faradaic constant [C/mol] | 96,485.34 |
| H2 molecular weight [kg/kmol] | 2.00 |
| Refilling time [min] | 20.00 |
| H2 required [kg] | 35.00 |
| | |
| Hydrogen production [kg/min] | 1.75 |
| | |
| Mass of H2 [kg/s] | 0.03 |
| Moles of H2 [mol/s] | 14.58 |
| Cell voltage [V] | 1.77 |
| Stack voltage [V] | 1,059.60 |
| Stack power [kW] | 762.91 |
| Nominal power [kWel] | 5,340.38 |
| Specific consumption [kWhel/kg] | 50.86 |

*Table 3 - Alkaline Electrolysis*

The specific consumption represents the system efficiency, that is a little higher for the alkaline cell. Both solutions can be performed; however, alkaline electrolysis is more feasible because it is already present in the market, while the PEM solution is less reliable, at the state of the art.

The hydrogen conditions at the end of the production are around 30 bars pressure and a temperature around 80°C since they are low-temperature technologies. The gaseous hydrogen is sent to *Germani* through a pipeline and then compressed and ready for the refilling.

## 4.2. STEAM REFORMING

Steam reforming process allows to produce hydrogen from the combustion of the methane. The input parameters are the quantity of methane and of heat to introduce.
First of all, considering an efficiency of the process of 70% and the chemical process, the amount of methane per day has been computed.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2$$

$$\eta = \frac{\dot{m}_{H_2} * LHV_{H_2}}{\dot{m}_{CH_4} * LHV_{CH_4} + \Delta H * \dot{n}_{H_2}} \rightarrow \dot{m}_{CH_4}$$

Given the lower heating value of methane equal to 50 MJ/kg, the reaction enthalpy of 0.165 MJ/mol, the moles of hydrogen produced per day equal to 875 and the lower heating value of hydrogen equal to 120 MJ/kg, the power production is about 1 MW, and the energy consumption of methane is around 83 MWh/day.

| | |
|---|---|
| Efficiency | 0.70 |
| LHV methane [MJ/kg] | 50.00 |
| Reaction enthalpy [MJ/mol] | 0.17 |
| Moles of H2 per day [mol/day] | 875.00 |
| LHV Hydrogen [MJ/kg] | 120.00 |
| Amount of heat [MJ/kg$CH_4$] | 10.00 |
| Amount of methane per day [kg$CH_4$/day] | 5,997.11 |
| Amount of heat per day [MJ/day] | 144.38 |
| Power production [kW] | 1,012.73 |
| | |
| MWh Methane [MWh/day] | 83.29 |
| Specific consumption [kWh$CH_4$/kg$H_2$] | 47.60 |

*Table 4 - Steam Reforming*

## 4.3. HYDROGEN CONDITIONING AND TRANSPORTATION

After the hydrogen production, the hydrogen conditioning and processing has been analysed. All the three solutions require the compression, to refill the truck fleet. The compressor is located nearby the *Germani* company, and it is connected to the plants through two different pipelines. The speed inside the pipeline is about 6 m/s, the diameter of 0.61 m, the length is about 1 kilometre. Thus, the distributed losses are negligible for this analysis, according to the results.

| | |
|---|---:|
| ΔP/L [Pa/m] | 0.033197 |
| λ | 0.012500 |
| ρ [kg/m$^3$] | 0.090000 |
| v [m/s] | 6.00 |
| Diameter [m] | 0.61 |
| ε [mm] | 0.05 |
| Lenght L | 1,000.00 |
| ΔP [Pa] | 33.20 |

*Table 5 - Pipeline Losses*

The compressor has to compress the hydrogen to the refilling pressure of 350 bars. Its energy consumption is the same for the three solutions, since the starting pressure does not change. Thus, the daily compression consumption has been computed. The consumption has been computed through an empirical formula.

$$Compressor\ consumption\ [\frac{MJ}{kg_{H_2}}] = 2.01 * (\frac{P}{P_0})^{0.3356}$$

| REFILLING STATION | PEM | ALKALINE | SMR |
|---|---|---|---|
| | | | |
| Number of vehicles per day | 50.00 | 50.00 | 50.00 |
| Mass refilled [kg] | 35.00 | 35.00 | 35.00 |
| H2 pressure [bar] | 350.00 | 350.00 | 350.00 |
| Empirical compression consumption [MJ/kg] | 14.35 | 14.35 | 14.35 |
| Refilling time [min] | 20.00 | 20.00 | 20.00 |
| | | | |
| Daily demand [kg/day] | 1,750.00 | 1,750.00 | 1,750.00 |
| Hydrogen production consumption [MWh/day] | 91.40 | 89.01 | 83.29 |
| Compression consumption [MWhel/kg] | 0.0039873 | 0.0039873 | 0.0039873 |
| Daily compression consumption [MWhel/day] | 6.98 | 6.98 | 6.98 |

Table 6 - Refilling Station

### 4.4. RESULTS

Taking all the factors into account, all the solutions can be implemented since the required hydrogen production is easily satisfied for the goal of the project.

Each application presents advantages and disadvantages for the designed purposes.

Comparing the two different electrolysis production systems, the dimensions of PEM are lower with respect to alkaline, resulting in a more compact system. In addition, the presence of a solid electrolyte avoids the formation of bubbles in PEM cells, while for the alkaline ones the flammability of hydrogen when it reacts with oxygen is a serious issue that implies more maintenance and safety measures. Then, the purity of the hydrogen is higher for the first solution thanks to the solid electrolyte. The separator of alkaline cells is not as effective as the solid electrolyte, indeed. Yet, PEM solution has a higher Faradaic efficiency, that depends on the number of electrons that move inside the system and represents the lost fraction of current in the process. The specific electricity consumption is a little higher for PEM, given the selected parameters. Higher current intensity implies higher power and thus higher consumption. However, the first systems are not already available for large scale projects, while alkaline solution is already implemented in some industries where the construction of huge dimensions plants is feasible.

In the project case, both production sites offer big spaces. Thus, both solutions are affordable from an energetical point of view. Nevertheless, economic and environmental analysis must be performed in order to evaluate the feasibility of the project.

Then, also steam reforming hydrogen production is possible since the requested amount of $H_2$ is easily satisfied. This solution is the most used and ready to implement nowadays since many industries have adopted this process. In the project case, it would decrease the amount of pollutants emitted by the steel production. In addition, the heat produced through the steel processing can be used for the hydrogen production, resulting in a more sustainable solution. However, steam reforming requires methane as input, that has to be bought from the grid. Unlike electrolysis is completely self-sustainable, steam reforming process is dependent from the external methane supplier.

In conclusion, for what concerns the specific energy consumption, the three solutions have similar values. PEM electrolysis is the most energy expensive with 52.2 kWh of electricity used per kilogram of hydrogen. Alkaline electrolysis has a lower specific consumption of roughly 3%. Steam reforming energy utilization is performed in terms of kWh of methane: 47.6 kWh correspond to 3.4 kilograms of $CH_4$ per each kilogram of hydrogen.

In this analysis, the energy consumption associated to the carbon capture is not computed due to the lack of data at the state of the art. However, in real cases about 10% of consumption should be considered for the system with CCS.

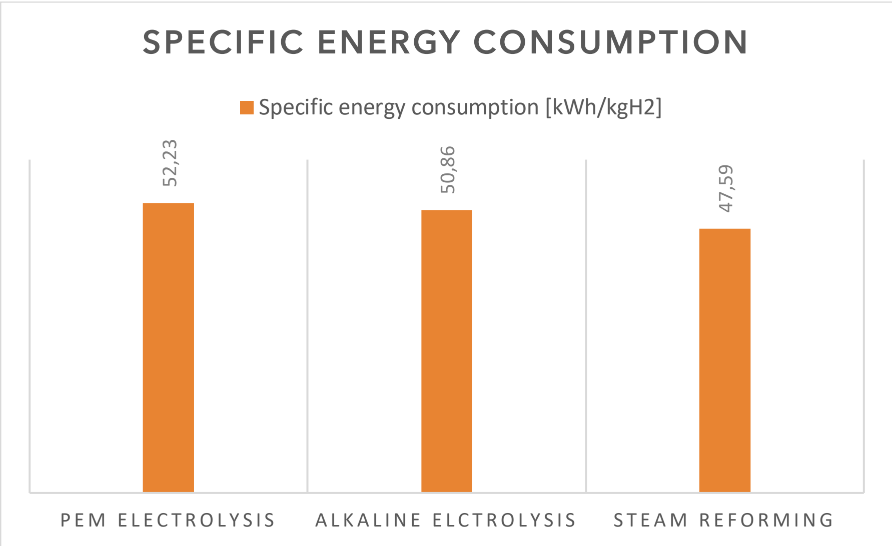



*Figure 18 - Specific Energy Consumption*

# 5. ECONOMIC EVALUATION

Since all the three solutions are feasible from an energetical point of view, the economical evaluation becomes crucial for the project purposes. The analysis is similar for both electrolysis and steam reforming processes, but some indices are different.

First of all, considering the electrolysis production, the Operating Expense (*OPEX*) has been computed, both for the variable and fixed terms. The *OPEX* is divided into variable and fixed, depending on what costs are considered. The variable takes into account the costs of raw materials, consumables, fuels etc., while the fixed includes the personnel and maintenance costs.

The variable *OPEX* is computed as the product between the amount of hydrogen produced and the electricity price. The cost of electricity is the lowest possible, since it is produced in the waste-to-energy plant by the same company. This is the first big advantage of electrolysis solution, since the supply phase is performed internally. The price is estimated around EUR 80 per MWh of electricity, according to the *GME* price of the previous year. The decision to use the data of year 2018 is due to the high electricity prices today. The mean value is around EUR 71 per MWh, but EUR 80 per MWh is chosen in order to consider the price variation during the year. The same date will use to identify the market price of methane.

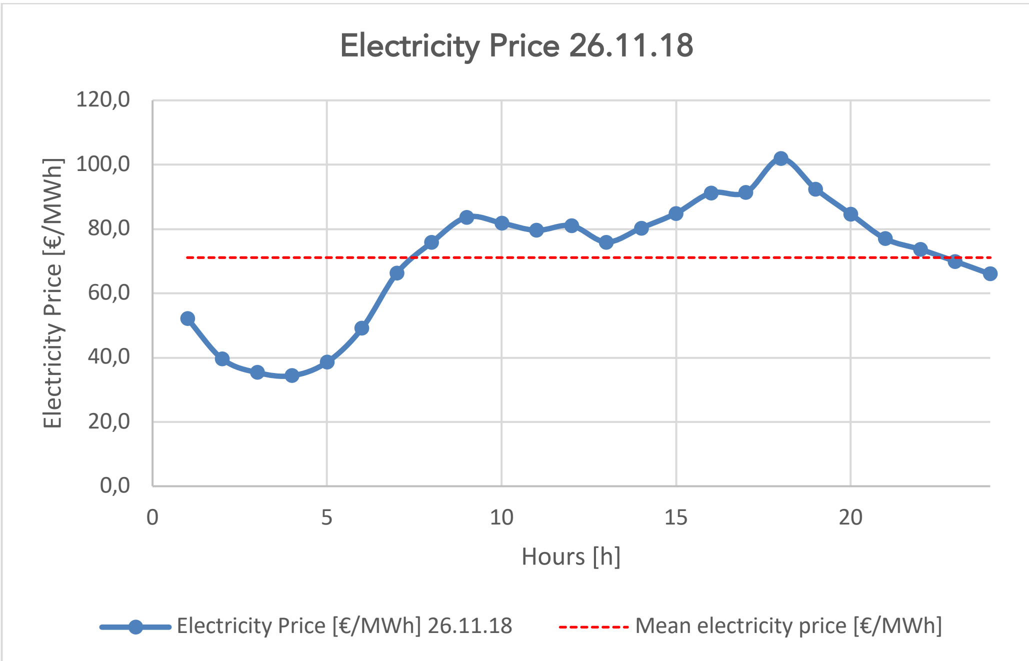



*Figure 19 - Electricity Price 26.11.18*

In addition, the *OPEX* related to the compression process is considered, computed as the product between the electricity price and the compressor consumption. The overall variable *OPEX* is about 3,000 k€ per year for both solutions. Alkaline costs are slightly lower due to the lower specific consumption.
Then, the investment costs are computed, multiplying the specific investment costs by the plant power production. Unlike the *OPEX*, investment costs are factually different since alkaline solutions are cheaper. The values have been chosen equal to EUR 1,500 per kW and EUR 700 per kW for PEM and alkaline plants, respectively. This results in distant costs, approximately EUR 8.2 million for the first and EUR 3.7 million for the second one.
The *CCF* (Capital Charging Factor) or *CRF* (Capital Recovery Factor) is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time and it is used to compute the *CAPEX*.
The *CAPEX* (Capital Expenditure) represents the cost of components, engineering, workers… referred to the initial investment. The *CCF* has been set equal to 10%, according to the state of the art.
Yet, the fixed *OPEX* is calculated as a percentage of the *CAPEX*. For PEM production, it is the 2%, while for the alkaline is around 4%, since the second solution requires more maintenance services.

| **COSTS** | **PEM ELECTROLYSIS** | **ALKALINE ELECTROLYSIS** |
|---|---|---|
| OPEX var,ee [k€/year] | 2668.97 | 2598.99 |
| OPEX var,methane [k€/year] | / | / |
| Purchase electricity price [€/MWh] | 80.00 | 80.00 |
| Methane cost [€/MWh] | / | / |
| Daily cost of Methane [€/day] | / | / |
| OPEX var,compr [k€/year] | 203.75 | 203.75 |
| Specific investment costs [€/kW] | 1500.00 | 700.00 |
| Investment costs [M€] | 8.23 | 3.74 |
| CCF | 0.10 | 0.10 |
| CAPEX [k€/year] | 822.63 | 373.83 |
| OPEX fix [k€/year] | 164.53 | 149.53 |
| OPEX factor | 0.02 | 0.04 |

*Table 7 - Electrolysis Costs*

The same approach has been followed for the cost computation of the steam reforming plant. The main difference is given by the *OPEX* related to the methane consumption and the investment costs. The variable *OPEX* due to the compression step is a little higher since the electricity price is considered equal to EUR 120 per MWh, because it has to be bought from the grid.

Then, the methane specific price is EUR 24.57 per MWh according to *GME* data 26/11/2018.

10/12/21, 12:19 GME - Esiti dei mercati - MGP-GAS - negoziazione continua

Esiti MGP-GAS

**sessione del: 26/11/2018**

| Prodotti | Prezzo (€/MWh) | | | | | | Volumi | |
|---|---|---|---|---|---|---|---|---|
| | first | last | min | max | rifer. | controllo | MW | MWh |
| MGP-2018-11-27 | 24,800 | 24,650 | 24,400 | 24,800 | 24,560 | 24,569 | 3.115 | 74.760 |
| MGP-2018-11-28 | - | - | - | - | - | 24,612 | - | - |
| MGP-2018-11-29 | 25,500 | 25,200 | 25,200 | 25,600 | 25,451 | 25,196 | 215 | 5.160 |
| **TOTALE** | | | | | | | **3.330** | **79.920** |

*Figure 20 - Methane Price 27.11.18*

The specific investment costs have been chosen equal to EUR 535 per kW and EUR 900 per kW for the system without CCS and with CCS, respectively, according to the *Techno-economic and environmental assessment* of hydrogen production based on natural gas steam reforming process paper. However, the assumption made to identify the investment costs of the SMR is that a reformer more powerful than 1MW is used for production. The hydrogen demand needed to refuel the *Germani* fleet would therefore represent only a portion of total production.

It results in EUR 0.54 millions of initial investment, since the plant dimension is relatively small, for the system without the carbon capture system. The system with CCS has higher investment costs, around EUR 0.91 million. The *CAPEX* is computed considering a *CCF* equal to 12% and the fixed *OPEX* are 1% and 1.5% (respectively for without and with CCS) of the *CAPEX*, since steam reforming is a reliable and low-maintenance production process.

| COSTS | STEAM REFORMING (NO CCS) | STEAM REFORMING (CCS) |
|---|---|---|
| OPEX var,ee [k€/year] | / | / |
| OPEX var,methane [k€/year] | 746.98 | 746.98 |
| Purchase electricity price [€/MWh] | 120.00 | 120.00 |
| Methane cost [€/MWh] | 24.57 | 24.57 |
| Daily cost of Methane [€/day] | 2,046.51 | 2,046.51 |
| OPEX var,compr [k€/year] | 305.63 | 305.63 |
| Specific investment costs [€/kW] | 535.00 | 900.00 |
| Investment costs [M€] | 0.54 | 0.91 |
| CCF | 0.12 | 0.12 |
| CAPEX [k€/year] | 65.02 | 109.38 |
| OPEX fix [k€/year] | 5.42 | 13.67 |
| OPEX factor | 0.01 | 0.015 |

*Table 8 - Steam Reforming Costs*

From the economical point of view, the Carbon Capture System apparently is not convenient; however, this system can result in incentives since a big amount of carbon emissions are avoided but this evaluation cannot estimate its possible amount of revenues. In addition, the costs related to the Carbon Capture System energy consumption are not evaluated, since the investment cost is almost two times than the system without and so it is the most relevant parameter for the price computation.

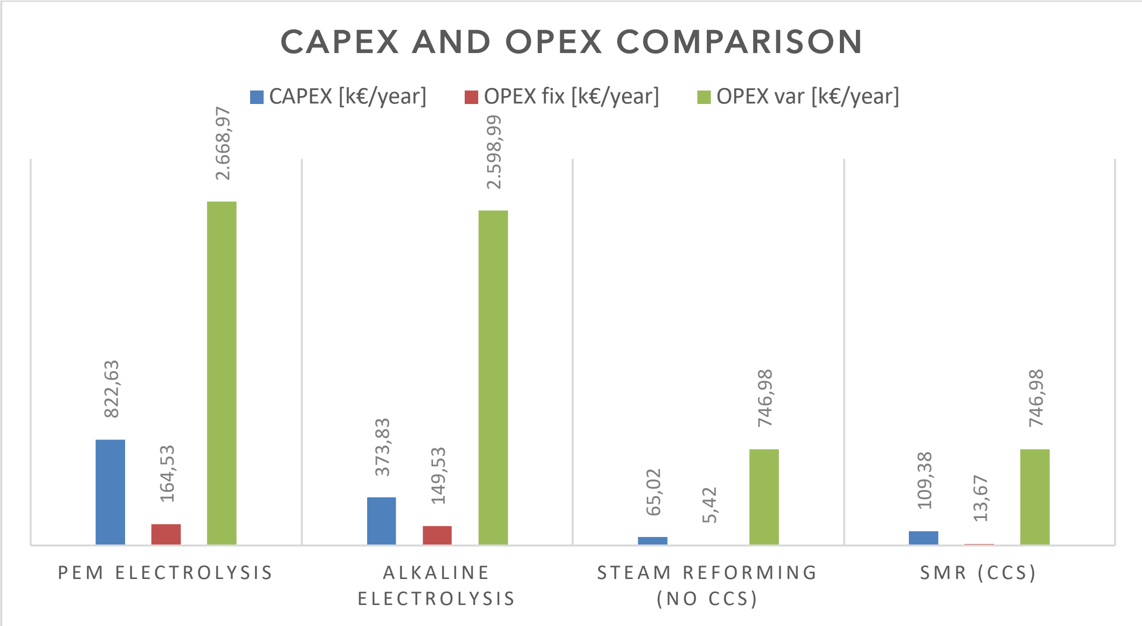



*Figure 21 - CAPEX and OPEX Comparison*

In conclusion, the Levelized Cost Of Hydrogen (*LCOH*) has been computed. This economic factor takes into account all the previous values and represents the cost per kilogram of hydrogen.

This index also includes the cost of the pipeline that transports the gaseous hydrogen from the production plant to the refilling station at the *Germany* company. According to the state of the art, its construction and maintenance increases the *LCOH* in EUR 0.2 per kilogram.

As the graph points out, the steam reforming without CCS solution is the most convenient, as expected. However, CCS system does not significantly affect the costs, increased only of around 9%. Electrolysis solutions are competitive, since the electricity provision really reduces the overall costs. Of course, as expected, the strength of the steam reforming is related to the costs at the state of the art; nevertheless, electrolysis advantages are mainly linked to its environmental sustainability.

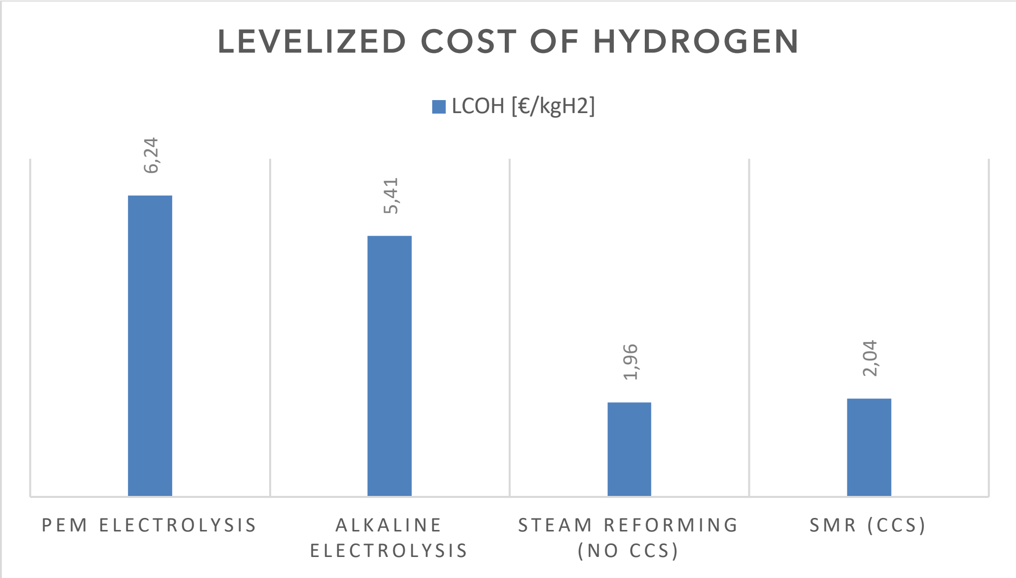



*Figure 22 - LCOH*

# 6. ENVIRONMENTAL EVALUATION

As mentioned above, the analysis of emissions has been carried out on two different levels.

The first one only focuses on direct carbon dioxide emissions from the hydrogen production processes (electrolysis and steam reforming), while the second also includes $CO_2$ emissions from the energy inputs production (electricity and methane).

In the bar chart below, it can be noticed that electrolysis processes have no direct emissions while the SMR contributes to the release of carbon. The efficiency considered for the $CO_2$ capture is 80%.

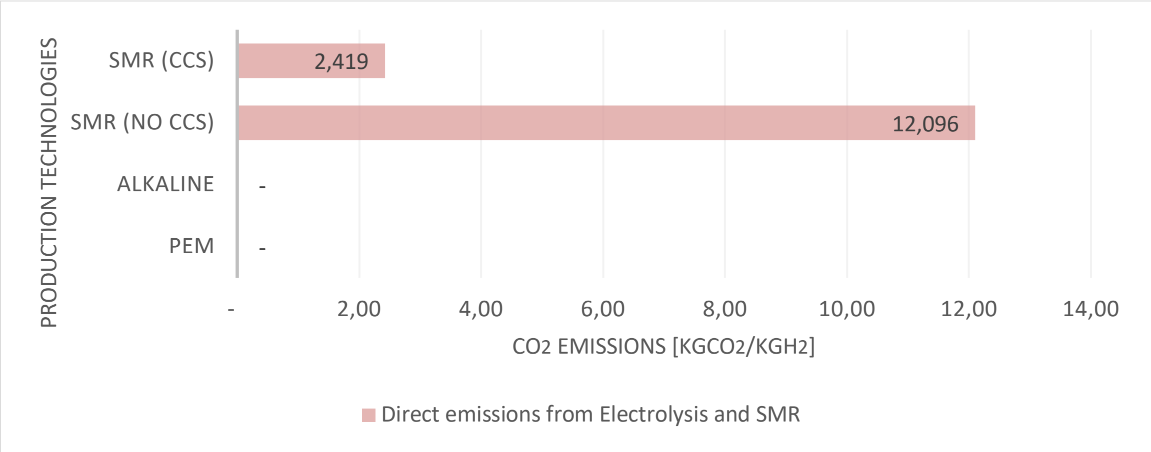



*Figure 23 - Direct Emissions H2 Production*

Extending the analysis to the whole supply chain, the situation looks substantially different.

The emissions associated with the waste-to-energy plant, that amount to around 470,000 tons $CO_2$, have been extracted from *a2a* 2019 environmental statement. This value must then be broken down between the production of heat and electricity. The division can be made either on the basis of the amount of energy produced or on the basis of the energy price. According to the first approach, electricity accounts for 43% of the entire production, while according to the second approach it accounts for 88%. As a consequence, heat accounts for 57% and 12% respectively, due to its low purchase price.

Thus, considering that the electrolysis process consumes 6% of the generated electricity, the total emissions for electrolysis amount to the values shown below.

PEM electrolysis

- 11,785.80 t$CO_2$/year for the first approach
- 24,355.06 t$CO_2$/year for the second approach

Alkaline electrolysis

- 11 498, 71 t$CO_2$/year for the first approach
- 23 761.78 t$CO_2$/year for the second approach

Therefore, the specific emissions in kilograms of carbon dioxide over kilogram of hydrogen are:

PEM electrolysis

- 18.45 kg$CO_2$/kg$H_2$ for the first approach
- 38.13 kg$CO_2$/kg$H_2$ for the second approach

Alkaline electrolysis

- 18.00 kg$CO_2$/kg$H_2$ for the first approach
- 37.20 kg$CO_2$/kg$H_2$ for the second approach

The steam reforming process uses electricity only for the compression of the gaseous hydrogen and therefore consumes 0.4% of the electricity produced by the waste-to-energy plant.
Using the previous approach, the emissions are listed below.

SMR (no CCS), SMR (with CCS)

- 835.929 t$CO_2$/year for the first approach
- 1727.43 t$CO_2$/year for the second approach

Specific emissions

- 1.31 kg$CO_2$/kg$H_2$ for the first approach
- 2.70 kg$CO_2$/kg$H_2$ for the second approach

The key input to the reforming process is methane, whose production chain emissions have been taken into account; this value amounts to 5.2 g$CO_2$/MJ HHV (288.6 g$CO_2$/kg$CH_4$), according to the chart below.

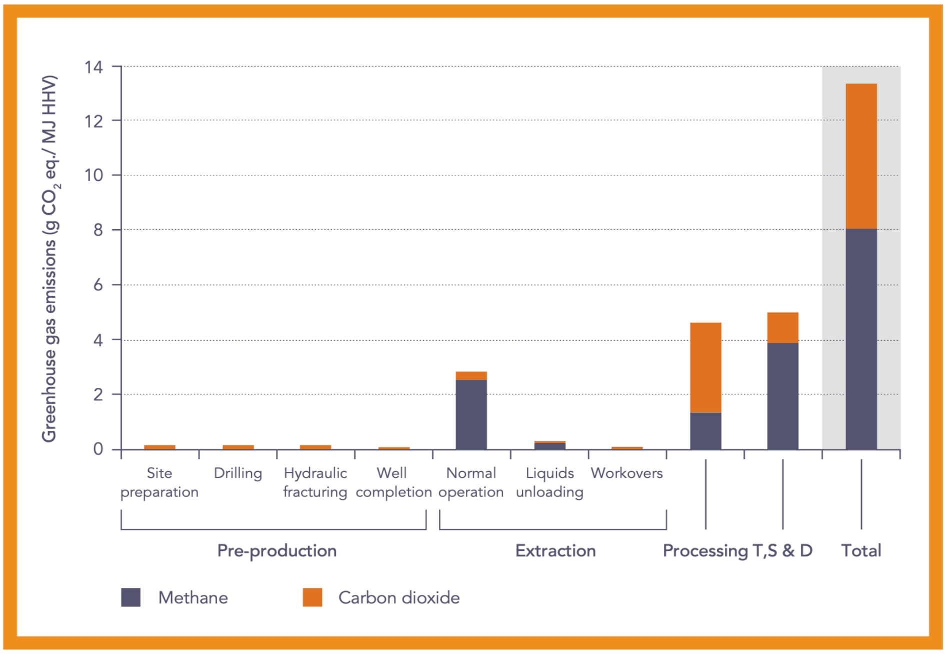



*Figure 24 - Methane Production Emissions*

Considering that the daily consumption of methane is 5997.11 kg, the $CO_2$ emissions are 631.73 t$CO_2$/year, which corresponds to 0.99 kg$CO_2$/kg$H_2$.

Direct emissions from methane combustion have been calculated according to the *JEC* report, which identifies a value of 100.8 g$CO_2$/MJ$H_2$ for steam reforming. Using this figure, the specific process emissions were calculated to be 12.096 kg$CO_2$/kg$H_2$ without CCS and 2.419 kg$CO_2$/kg$H_2$ with CCS.

The following graphs summarize the final results of the analysis.

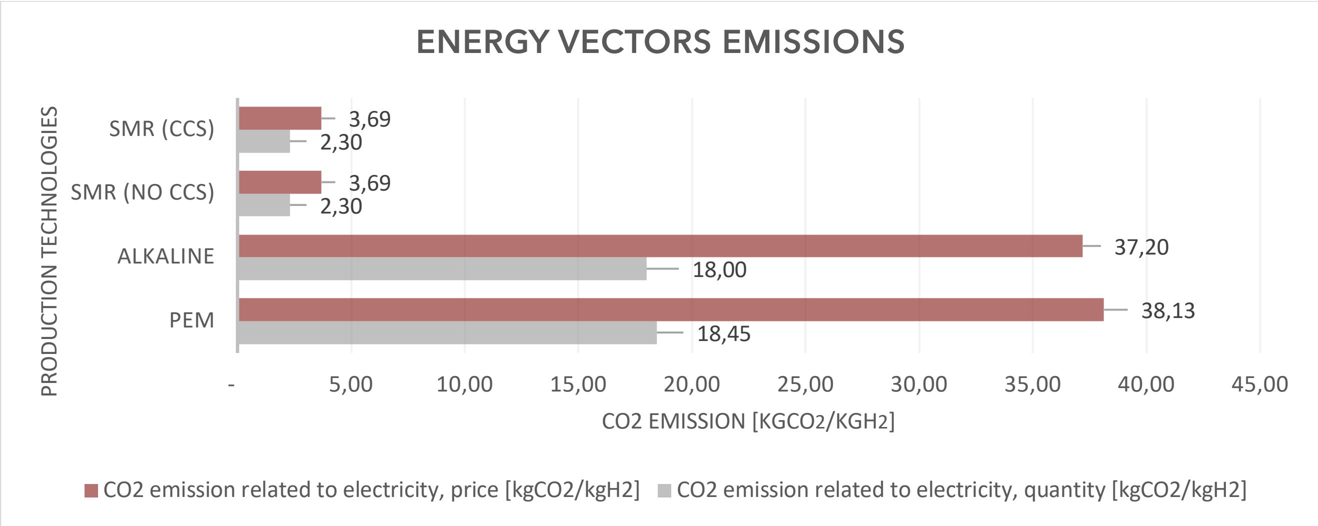
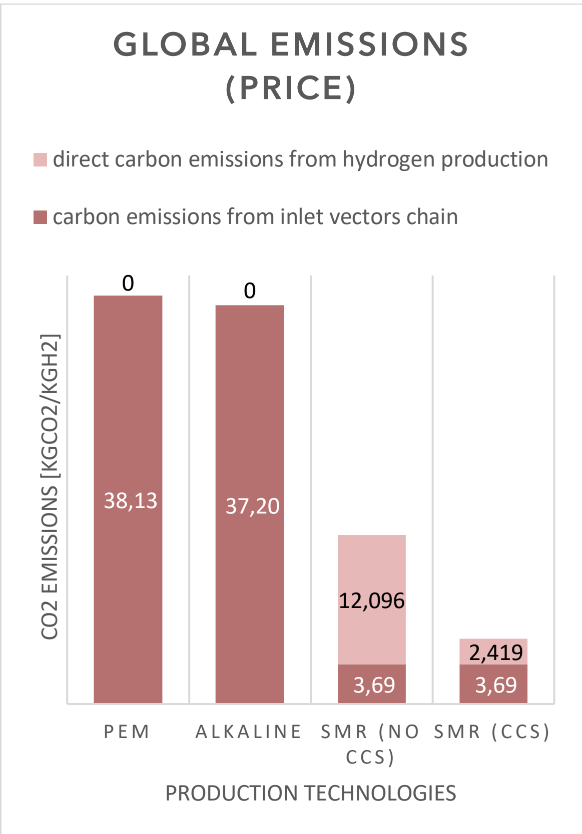



*Figure 25 - Energy Vectors Emissions*



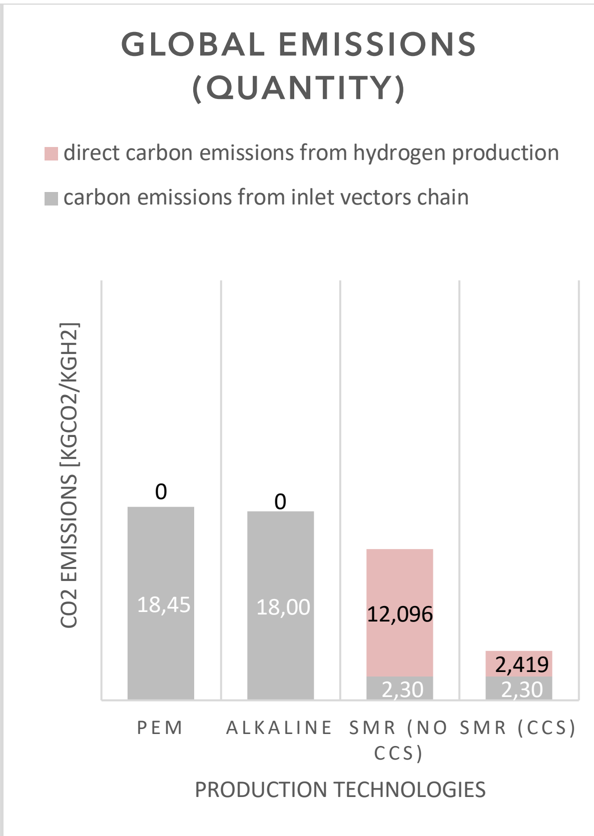




*Figure 26 - Global Emissions – Price*

*Figure 27 - Global Emissions - Quantity*

Taking all these factors into account, steam methane reforming production with CCS represents the best solution as far as concerns the emissions. Electrolysis, on the other hand, is characterized by the highest emissions in both the quantitative and economic approaches.

The emissions associated with heat production for SMR have been neglected since it represents a secondary step in *AlfaAcciai* steel processing and there are not enough data for an appropriate estimation. Therefore, these emissions must be taken into account in the environmental evaluation of the project, since they would significantly contribute to the total emissions related to the steam reforming production process.
However, this heat, if not used to produce hydrogen, would be dispersed into the atmosphere as at the current situation.

According to the normative, the mentioned solutions can be classified into:

- Green hydrogen: PEM and alkaline electrolysis;
- Blue hydrogen: steam reforming with carbon capture systems;
- Grey hydrogen: steam reforming without carbon capture systems.

Although this classification would seem to contradict the results of the analysis carried out so far, some clarifications are in order.
Hydrogen produced in a waste-to-energy plant is not a totally green solution, as electricity is produced by burning waste, which also generates carbon dioxide. Legislation is in the making and there is currently no clear rule for classifying hydrogen produced by this process. However, if the hydrogen produced by this kind of electrolysis plant were to fall under the green classification, the system could get incentives, improving its economical indices.
In addition, steam reforming could increase its classification rate, using biomethane as inlet vector; nevertheless, it would negatively affect its economical evaluation and positively its global emissions evaluation.
The previous considerations could be used for further analyses.

# 7. CONCLUSIONS AND DISCUSSION

The main objective of this study is to compare the current diesel fleet indices with those of the hydrogen proposal. As previously mentioned, *Germani* company currently has a fleet of 150 diesel-powered *Mercedes ACTROS Euro VI* vehicles; the proposal is to replace them with an equal number of hydrogen-powered *Hyundai XCIENT* fuel cell vehicles.

From a consumption point of view, the two technical solutions have the following features:

*Figure 28 - Mercedes ACTROS*

| **Mercedes ACTROS TRUCK** | |
|---|---|
| tank [l] | 900.00 |
| density [kg/l] | 0.84 |
| fuel consumption [l/km] | 0.40 |
| fuel consumption [kg/km] | 0.33 |
| fuel consumption [$MJ_F$/km] | 14.50 |
| driving range [km] | 2,250.00 |
| LHV [$MJ/kg_F$] | 43.40 |

*Table 9 - Mercedes ACTROS Parameters*

| **Hyundai XCIENT FCEV TRUCK** | |
|---|---|
| tank [$kgH_2$] | 35.00 |
| driving range [km] | 400.00 |
| fuel consumption [$kgH_2$/km] | 0.06 |
| fuel consumption [$MJH_2$/km] | 10.50 |
| LHV [$MJH_2$/kg] | 120.00 |

*Table 10 - Hyundai XCIENT Parameters*


*Figure 29 - Hyundai XCIENT*

Subsequently, using the fuel consumption in MJ over km and vehicle range as inputs, the solutions were evaluated from an emission (WTW analysis) and economic point of view.

The results have been organized:

- Considering one truck

| 1 truck | | | | | | | |
|---|---|---|---|---|---|---|---|
| Energy carrier | Production Technology | Truck consumption [MJ/km] | Truck autonomy range [km] | WTT [gCO2/km] | TTW [gCO2/km] | WTW [gCO2/km] | cost of fuel [€/km] |
| H2 | ELECTROLYSIS (PEM) | 10,50 | 400,00 | 1.614,49 | - | 1.614,49 | 0,55 |
| | ELECTROLYSIS (ALKALINE) | 10,50 | 400,00 | 1.575,17 | - | 1.575,17 | 0,47 |
| | STEAM REFORMER (NO CCS) | 10,50 | 400,00 | 1.259,45 | - | 1.259,45 | 0,17 |
| | STEAM REFORMER (CCS) | 10,50 | 400,00 | 412,73 | - | 412,73 | 0,18 |
| DIESEL | REFINERY PROCESS | 14,50 | 2.250,00 | 202,94 | 1.061,08 | 1.264,02 | 0,28 |

*Table 11 - Comparison - Single Truck*

- Considering one truck over a year

| Analysis over 1 year for 1 truck | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Energy carrier | Production Technology | Truck consumption [GJ] | Truck autonomy range [km] | Average distance traveled [km] | WTT [kgCO2] | TTW [kgCO2] | WTW [kgCO2] | Cost of fuel [€] |
| H2 | ELECTROLYSIS (PEM) | 3.150,00 | 400,00 | 300.000,00 | 484.348,08 | - | 484.348,08 | 163.874,78 |
| | ELECTROLYSIS (ALKALINE) | 3.150,00 | 400,00 | 300.000,00 | 472.549,53 | - | 472.549,53 | 141.938,93 |
| | STEAM REFORMER (NO CCS) | 3.150,00 | 400,00 | 300.000,00 | 377.834,78 | - | 377.834,78 | 51.402,44 |
| | STEAM REFORMER (CCS) | 3.150,00 | 400,00 | 300.000,00 | 123.818,78 | - | 123.818,78 | 53.564,55 |
| DIESEL | REFINERY PROCESS | 4.348,68 | 2.250,00 | 300.000,00 | 60.881,52 | 318.323,38 | 379.204,90 | 84.000,00 |

*Table 12 - Comparison - Single Truck Single Year*

*The average distance traveled has been computed considering 12 daily working hours, an average speed of 80kmph and 300 working days in a year.

- Considering the total fleet over a year

| Analysis over 1 year for the entire fleet | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Energy carrier | Production Technology | n° of vehicles | Truck autonomy range [km] | Average distance traveled [km] | WTT [tCO2] | TTW [tCO2] | WTW [tCO2] | Cost of fuel [M€] |
| H2 | ELECTROLYSIS (PEM) | 150,00 | 400,00 | 300.000,00 | 72.652,21 | - | 72.652,21 | 24,58 |
| | ELECTROLYSIS (ALKALINE) | 150,00 | 400,00 | 300.000,00 | 70.882,43 | - | 70.882,43 | 21,29 |
| | STEAM REFORMER (NO CCS) | 150,00 | 400,00 | 300.000,00 | 56.675,22 | - | 56.675,22 | 7,71 |
| | STEAM REFORMER (CCS) | 150,00 | 400,00 | 300.000,00 | 18.572,82 | - | 18.572,82 | 8,03 |
| DIESEL | REFINERY PROCESS | 150,00 | 2.250,00 | 300.000,00 | 9.132,23 | 47.748,51 | 56.880,73 | 12,60 |

*Table 13 - Comparison - Entire Fleet Single Year*

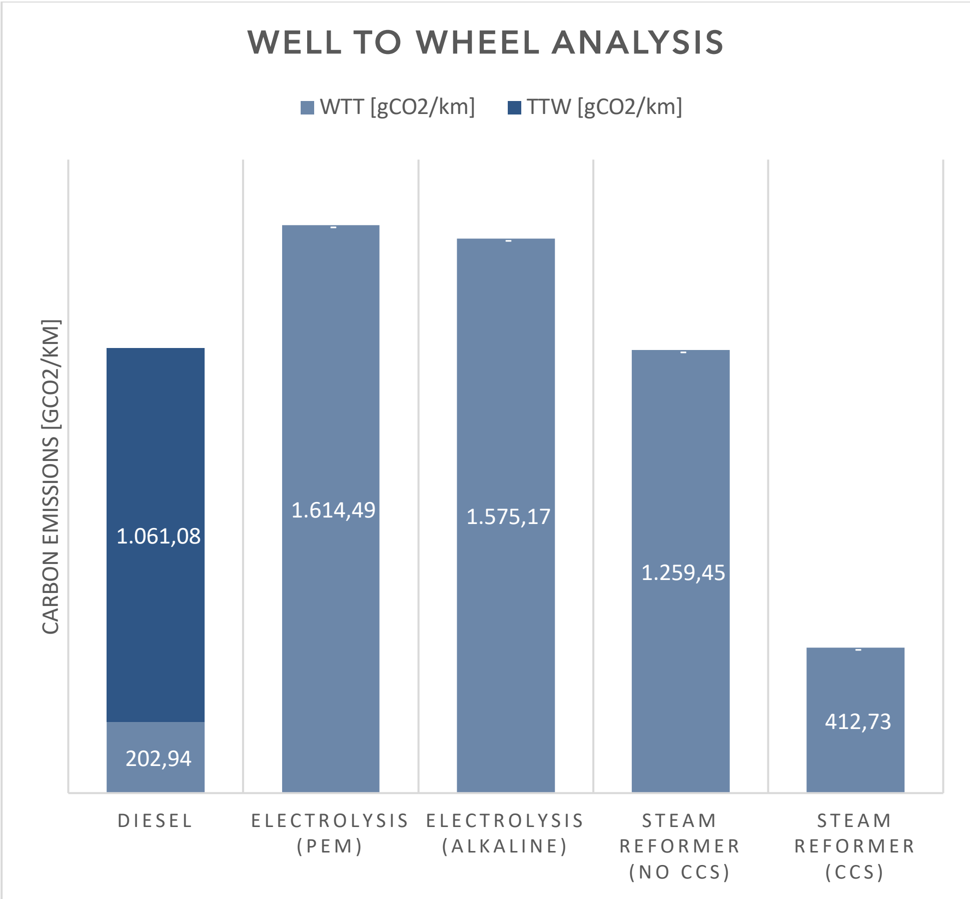



*Figure 30 - Well To Wheel Emissions*

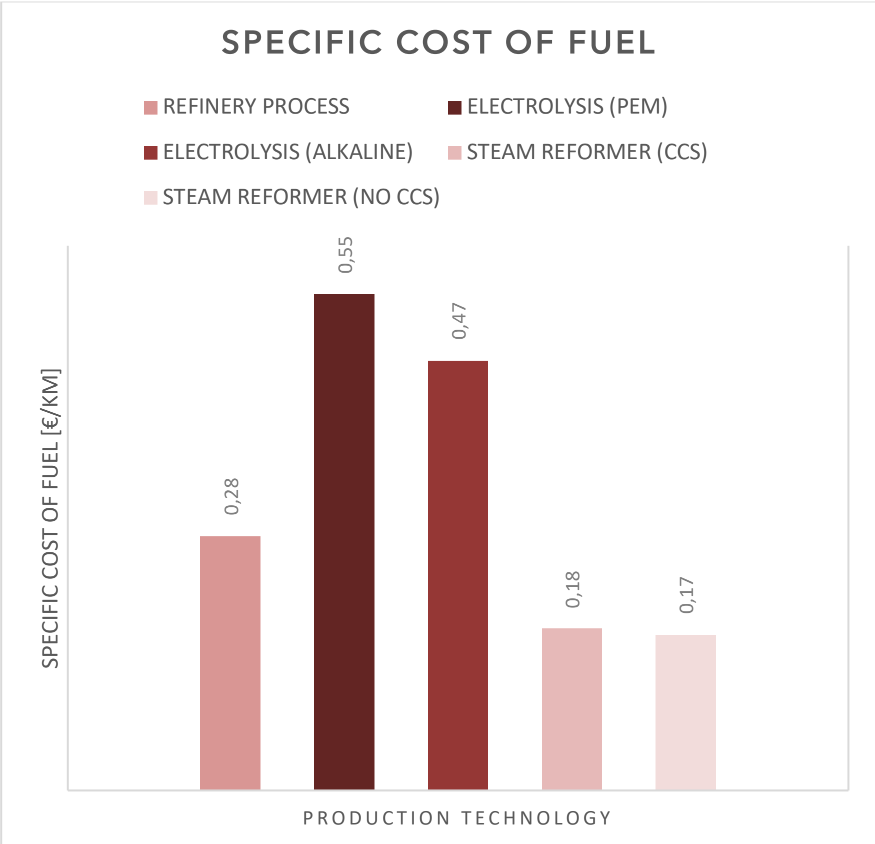



*Figure 31 - Specific Cost of Fuel*

According to the previous chart, the solution that produces the lowest emissions seems to be the SMR hydrogen production with CCS. However, the values cannot be compared with the electrolysis ones, since the emissions related to the electricity production through the waste-to-energy plant, derive from the combustion of the organic fraction of the waste. Differently, the emissions associated to SMR derive completely from a fossil source.

For Diesel, the fact that emissions are lower than electrolysis technologies is justified by the fact that the whole WTW process is optimized due to the maturity of the technology.

Also in this case, the carbon dioxide emitted comes from a fossil source and is a worse alternative than the carbon dioxide emitted from the treatment of organic sources.

Furthermore, for the electrolysis technologies (PEM and alkaline), which are still in an experimental phase, there is a lot of room for improvement, such as increasing the efficiency of the processes.

Economically speaking, SMR hydrogen represents the most effective solution, both with and without CCS, since the difference is not relevant.

On the other hand, hydrogen produced by electrolysis is the most expensive alternative, as expected from the economic analysis. Nevertheless, considering a more complete analysis, SMR costs should be increased due to externalities, because of the fossil carbon emissions.

Considering a penalty from EUR 85 to EUR 100 per ton of $CO_2$, according to the *Emissions Trading Scheme*, the price of SMR hydrogen increases, as reported below.

| | | | |
|---|---|---|---|
| Cost of emissions [€/ton$CO_2$] | 85.00 | 100.00 | 285.14 |
| Cost added to SMR no CCS [€/kg$H_2$] | 1.11 | 1.31 | 3.45 |
| Cost added to SMR CCS [€/kg$H_2$] | 0.29 | 0.34 | 3.37 |

*Table 14 - Penalised Costs*

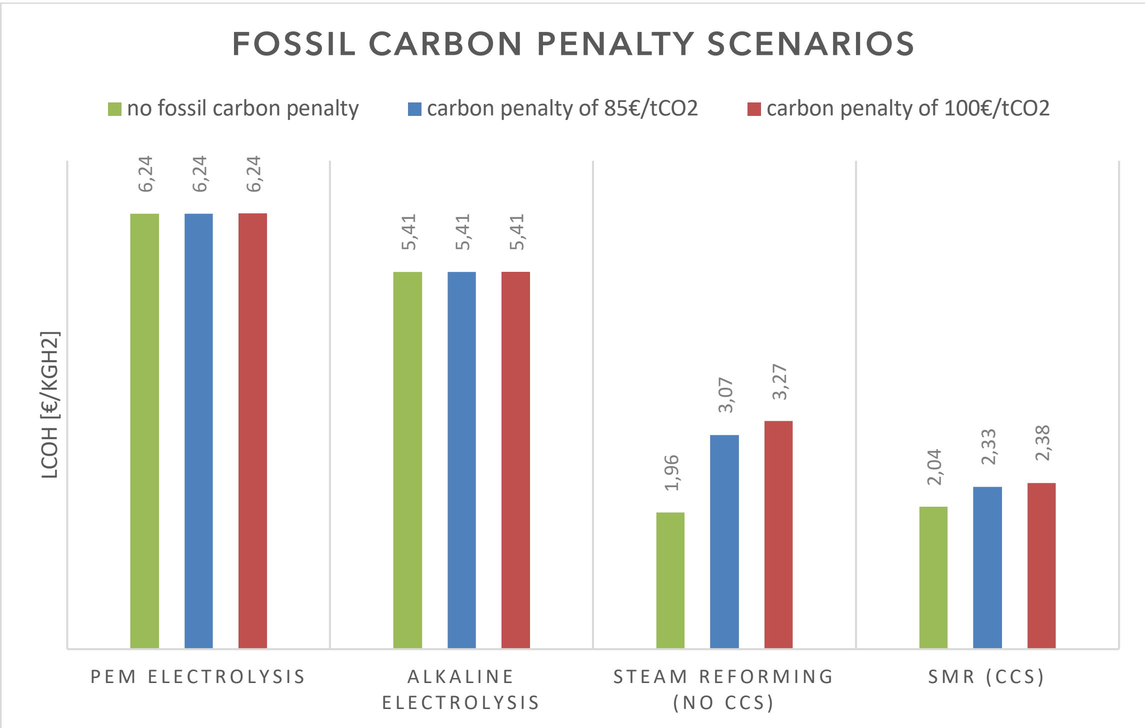



*Figure 32 - Fossil Carbon Penalty Scenario*

In addition, the penalty to reach an equal price for all the production processes would be of EUR 285.14 per ton of carbon dioxide emitted. Thus, SMR reforming production, at the state of the art, is still the most convenient alternative.

Diesel production costs have been estimated around EUR 0.7 per liter, since for all the solutions taxes and excise duties have not been considered. Therefore, Diesel solution appears to be inconvenient with respect to SMR hydrogen without penalties. However, since diesel trucks driving range is almost six times than the hydrogen trucks, the new solution would affect negatively the logistic and management process, due to the several refills needed. In addition, at the state of the art, the hydrogen grid is not developed in Italy and would need huge financial investments.

As mentioned before, since hydrogen produced by electrolysis is green, by steam reforming with capture is blue, and by steam reforming without capture is grey, electrolysis is the most sustainable technology, even if the global emissions are higher because the waste-to-energy plant uses only the organic fraction of the waste.

Taking all the factors into account, the goal of the project is satisfied, since all the solutions are feasible both from an energetical and economic point of view. Thus, the two alternatives are:

1) Steam reforming
2) Electrolysis

| | **Steam Reforming** | **Electrolysis** |
|---|---|---|
| TRL (Technology Readiness Level) | Widespread | Less ready |
| Normative Classification | Blue/grey | Green |
| Economic Evaluation | Cheaper but with penalties | Less cheap but with incentives |
| Local emissions | High (CH4 combustion) | Zero |
| Global emissions | Lower | Higher |
| Input source | Fossil | Organic fraction of waste |

*Table 15 - Steam Reforming - Electrolysis Comparison*

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