Hydrogen for Electricity: Technical and Normative Preliminary Analysis

Paper No. PCIC Europe EUR23_13

Roberto Sebastiano Faranda
Politecnico di Milano
Via La Masa, 20156 Milano
Italy

Kim Fumagalli
Politecnico di Milano
Via La Masa, 20156 Milano
Italy

Cosimo Menici
Piemme Energia
Via de Lemene, 20151 Milano
Italy

Abstract - Hydrogen is an energy vector that could help reaching the CO_2 neutrality before 2050. It has a very high potentiality to be exploited in many sectors such as automotive, energy production and storage. Hydrogen has an elevated energy density per unit of mass (much higher than the natural gas one), it does not produce pollutants (when it is used in electrolyser it allows to generate only electricity and water), it has a very low volume energy density. The hydrogen storage sector is the main topic of this study: an easily movable plug-in system is designed inside a container to use the additionally electricity produced with renewable sources – when the available generated power is higher that the load demand – to generate gaseous hydrogen in electrolyser that will be compressed until almost 700bar, stored in very high-pressure tank, and converted, whenever is needed, in electricity using a 15kW fuel cell stack. In particular, the purpose of this Paper is the analysis of the components contained in the system (15kW), with a focus on the electrolyser and fuel cell technologies, and a market analysis of the whole elements necessary in this type of system. Moreover, standards and national Directives related to hydrogen are proposed to better explain what is needed by this technology to spread and ATEX Directive is explained in relation with hydrogen use. Efficiencies of the whole system are computed with design parameters in the case of combined heat and power generation, obtaining that it is possible to recover about one fifth of the power inlet in the system. Finally, a qualitative analysis is presented where the performances of the whole system (from the renewables' electricity consumed to produce hydrogen until the electricity generated using hydrogen) are showed related to the variation of the main operative factors: temperature, pressure and humidity.

Index Terms — Hydrogen, fuel cell, storage system, renewables ATEX, IECEX, Ex area.

I. INTRODUCTION

The continuous population increase and the high level of globalization and industrialization that will be reached in the next future, will rise the global energy demand by 50% until 2030, according to the International Energy Agency (IEA). While today most of the energy demand is met using fossil fuels and generating pollution – coal, oil, natural gas cover about 80% of the total energy supply – the main challenge is the clean energy production using renewable sources as wind, sun, water flow, etc… [1]. Furthermore, the increase of energy demand leads to higher pollution generation and global warming, resulting in higher number of temperature anomalies and mean temperature increase as showed in Figure 1, where it is clearly visible that temperature is over 1°C higher than 50 years ago, leading to the melting of glaciers and the rise of the sea level: significant effects of global warning [2].

In the last 20 years solar and wind are spreading a lot thanks to the development of new materials and configurations and with the help of incentives from governments. Since one of their main troubles is the difficult in the energy production prediction, lot of available energy, if not needed in the exact moment, is wasted without an appropriate storage system. Here is the potential of hydrogen: a new way to store big quantity of energy with the possibility to use it rapidly and without pollution generation or any carbon emission but only water as a by-product.

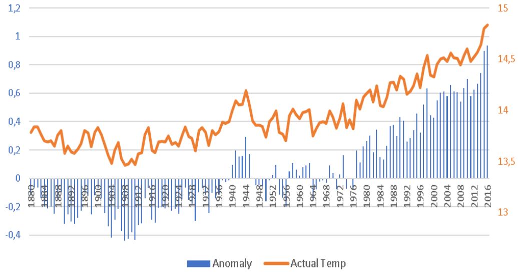


Figure 1: Temperature and anomaly between 1880 and 2016

The goal of this Paper is to define and analyse a small size plant in which the hydrogen is produced with electrolyser (consuming electricity from renewable power plants), stored, and used to generate electricity and heat when needed. Moreover, a normative preliminary analysis of the system is provided.

II. HYDROGEN

Hydrogen is the most abundant element in the Earth, colourless, nontoxic, explosive and odourless, with a very high energy content per mass unit (140MJ/kg, nearly 3 times the one of gasoline ~50MJ/kg) but is not possible to find it in nature as free element as it is always combined with others, like oxygen in water or carbon in hydrocarbons: to obtain pure hydrogen we have to isolate it using lot of energy. Hydrogen is so classified not as energy source but as energy carrier: a substance that can be transported and can produce energy, but only because it contains energy given by another system.

A. Hydrogen production

The hydrogen demand is increased more than four times in the last 40 years, reaching today more than 90 million tonnes per year. This is mostly produced starting from fossil fuels, generating pollution and CO_2 emissions. Looking at the Net Zero Emission by 2050 Scenario (NZE), globally the share of hydrogen in the total final energy consumption would be around 2% by 2030 and 10% by 2050 (currently it is 0.1%) and mostly would be obtained with low-carbon technologies as electrolysis or fossil fuels with Carbon Capture, Utilisation and Storage (CCUS).

The versatility of hydrogen permits to generate it using all types of energy sources (coal, oil, natural gas, biomass, renewables and nuclear) through a very wide variety of technologies. The processes used to produce hydrogen can be divided in:

- ✓ *thermochemical process*: these make use of chemical and/or thermodynamical reaction to obtain hydrogen starting from organic material as natural gas, coal, biomass (e.g. Steam gas reforming, coal gasification and partial oxidation);
- ✓ *electrolytic process*: electrolyser uses the electricity to split water in hydrogen and oxygen;
- ✓ *direct solar splitting from water process*: this new technology produces hydrogen from water directly using the energy from sunlight;
- ✓ *biological process*: bacteria and algae produce hydrogen by biological reaction exploiting sunlight or organic material.

The common and most used ones are Steam Gas Reforming (SGR), Coal Gasification, Partial Oxidation (POX) and Water Electrolysis [3] [4]. For the scope of this Paper, Water Electrolysis will be the only one analysed below.

Water Electrolysis allows to obtain hydrogen from water and electricity. In its simplest form, the water is splitted in hydrogen and oxygen (a by-product) thanks to an electrical current passing through a pair of electrodes. Typical low temperature electrolysers have very good system efficiency but with a higher H_2 cost, about 10$/kg: this aspect reflects also in the share of this technology in the hydrogen production, as electrolysis account only for the 4% of the total production. Different electrolysis technologies are available today that differ in materials, temperature, cost, and efficiency [5] [6]:

- ✓ Alkaline electrolyser. Used in commercial application up to MW range, it is characterised by low operating pressure, limited current density, low energy efficiency (70-80%), working temperature between 30-80°C and also low capital cost compared to other electrolysers due to nickel use;
- ✓ Proton Exchange Membrane (PEM) electrolyzer. Compared to alkaline electrolyzer it has lower gas permeability, lower thickness, high pressure operation, high proton conductivity, compact design, high current density, high efficiency (80-90%), low temperature, fast response, but expensive catalysts used, composed by materials like noble metals;
- ✓ Solid Oxide Electrolysis Cell (SOEC). It allows to obtain ultra-pure hydrogen with the highest efficiency (90-99%) operating at high pressure and high temperature (500-850°C) and utilizing steam water and ceramic elements as electrolyte. Nowadays main problems with SOEC are the low stability of the system and the high components degradation.

B. *Hydrogen applications*

Thanks to its high versatility, hydrogen can be used in almost all the sectors. Today its demand comes mainly from industry sectors (chemical production as ammonia and methanol production and steelmaking direct reduced iron process) and from refineries (desulphurisation). Other applications that are expected to grow up in the future are: transport, heating and hot water for buildings, and power generation.

C. *Hydrogen storage systems*

Storage systems connected with hydrogen technologies are fundamental for the spread of this clean gas in the future. As the share of variable renewable energy sources increases, systems to store the electricity produced by, in particular, solar and wind power plant become necessaries to obtain a sustainable and flexible electricity system. One of the big pros of hydrogen is the wide range of storing capacity, as it can be saved in hundreds of meter cubes area or in a little tank with the size of a mobile phone battery. The most common way to store it is the compression inside cylinder vessel, where pressurizing gaseous hydrogen until 700bar means increase its density up to 40 gH_2/L so 400 times the one at standard conditions.

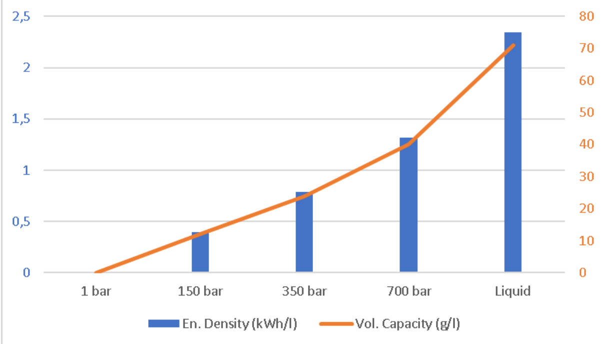


Figure 2: Hydrogen energy density and volumetric capacity

III. FUEL CELL

Fuel Cell (FC) is a thermodynamic device that converts the energy of a fuel directly into electricity and heat, without passing through thermal cycles. A fuel cell is made by two electrodes, cathode (positive) on the air side and anode (negative) on the fuel side. Its operation is based on electrochemical reaction as Redox, consuming part of reactants to give, as product, electric power: in our case, the hydrogen that represents the fuel is oxidized while the oxygen is reduced producing electricity and water as by-product. It can be applied in a very wide range of power, so in different fields: backup power, long-term energy storage with hydrogen reservoir, and power source for buildings and vehicles. Fuel cell process differs from one FC type to another one due to the properties of their main components (anode, cathode, catalyst, and electrolyte): the most used and promising are Solid Oxide Fuel Cell (SOFC) and Polymer Electrolyte Membrane Fuel Cell (PEMFC) for their wide range of applications, given by the possible stack size, and for the high efficiency.

PEM fuel cells have high power density and efficiency, operate at low temperature, around 80-90°C, have a quick start as the warm-up time is less, so wear out the system components less. The main drawbacks are represented by the required noble-metal for the catalyst, as platinum is expensive and suffers the carbon monoxide poisoning and the water management to avoid water flooding.

SOFC power output can be up to 2MW and its operational temperature can vary a lot, working between 500°C until 1,000°C: this aspect makes SOFC promising for co-generation systems with very high efficiency. SOFC does not need an expensive precious-metal catalyst and it can use a wide range of fuels, but drawbacks of high temperature are the slow start up and the need of thermal shielding to keep the heat and to be safe [7].

IV. MARKET ANALYSIS OF COMPONENTS

The stationary power plant (nominal power 15kW) studied in this Paper consists mainly in electrolyser, compressor, storage system, and fuel cell systems, plus the Balance Of Plant (BOP) components. The BOP comprises all the remaining elements like pumps, valves, humidifiers, filters, piping, heat exchangers, instrumentation, controls, manifolds, and power subsystems such as converter and inverter. The choice of each component is made taking care the design of the system that we want to assemble, the energy consumption and also the cost in order to create a power system attractive to customers in the energy market.

The electrolyser is the first important component that compose the base of the whole system: high purity hydrogen is produced with the consumption of pure water and electricity generated, in an ideal situation, by renewable power plants. The size of chosen electrolyser is given by the quantity of hydrogen needed to gain the nominal output power with fuel cell stack. We opted for a high-pressure Alkaline electrolyser, because this is a very well-known technology and its presence in the market is nowadays more widespread than for PEM and SOEC technologies. This solution allows to obtain a nominal hydrogen flow equal to 20Nm^3/h at 30bar pressure yet. The energy consumption at nominal hydrogen flow rate is equal to 4.5kWh/Nm^3 and this model allows to obtain a fast dynamic response, thus the perfect solution for coupling with renewable energies. It accounts for about the 30% of the system total price, so the selection is crucial also in term of capital investment.

The hydrogen produced in the electrolyser needs to be compressed before storing it, thus a compressor is mandatory to be present in this hydrogen system. The quantity of energy that can be stored increases from 3.3kWh/m^3 at ambient pressure to 1,478kWh/m^3 at 700bar but its compression requires the use of about 10% the energy available in the gas. Air-driven gas booster are very simple elements and occupied small space with the ability to gain up to 10 times the inlet hydrogen pressure with a stage. Moreover, the maintenance is very simple, there is no need of electrical or cooling connections and it gains gas purity, only consuming a low-pressure air flow. In order to compress the project nominal value of 12Nm^3/h until 700bar hydrogen pressure starting from 30bar, two air-driven gas boosters placed in series are chosen with a volumetric efficiency of 85%. The energy expenditure is around 5.5kWh, while the cost of the whole compression system is nearly the 15% of the total investment.

The high-pressure vessel is the device where hydrogen is stored, placed after the compressor system and before the fuel cell stack. Where the hydrogen production is not too low, high-pressure vessel is selected as it is the simplest technology in the market and lot of companies in the hydrogen field produce this type of storage system. Type IV cylinders are the best decision in term of safety, high durability and also lightweight as they are produced in composite and carbon fibre, with a cost that accounts for about the 15% of the total investment. The model chosen has a working pressure of 700bar with a hydrogen capacity of about 10kg of hydrogen, resulting in more than 9 hours of operation at rated power of fuel cell.

Fuel cell stack is the main component of the system because it converts the hydrogen produced and oxygen in electricity without any type of pollutants emission but with only water and heat as by-products. The technology chosen is the PEM fuel cell thanks to its simplicity, high efficiency and low temperature working condition. In particular three modules of 5kW are placed in parallel in order to gain a nominal power equal to 15kW. The hydrogen consumption is equal to 0.804Nm3/kWh, that means about 12Nm^3/h (equal to around 1kgH_2/h) for the whole 15kW stack. The price for these three modules is similar to the electrolyser one, so it accounts for around the 30% of the whole system cost.

Balance Of Plant consists of all the other components that are necessary to run the whole system: pipes, valves and manifolds, security/control systems, pumps and blowers, heat exchangers, humidifiers, separators, filters, sensors, ventilation system, converter and inverter (Power-Conditioning Unit). All these marginal systems that are part of the BOP account for about the 10% of the initial investment.

V. SYSTEM ANALYSIS

This paragraph has the task of explaining how the whole structure is composed and, in particular, the analysis of the three main modules in which it can be subdivided: production, represented by the electrolyser; storage, so compressor that pressurize the hydrogen; conversion as the fuel cell stack. An accurate plant scheme is showed in Figure 3, that illustrate an example of the hydrogen power plant under study.

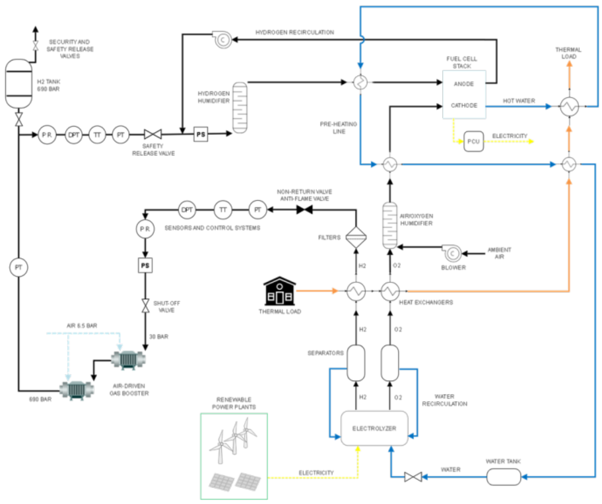


Figure 3: Hydrogen power plant Scheme

A. Production module

It is composed, among others, mainly of the electrolyser, the heat exchanger, the filters, and the inlet water and electricity. The functioning of this module is characterized by the inlet flow of water in the electrolyser and the used electricity, both consumed to produce hydrogen on cathode side, and oxygen as by-product on anode side. These two gases are collected separately and then, in specific separators, are divided from the liquid electrolyte that comes back in the electrolyser: the inlet water in so regulated taking into account the quantity of electrolyte that return from the separators. The next component is the heat exchanger, to cool down the gases produced in electrolyser before entering in the system. This action allows to obtain a gas flow at about ambient temperature and also to gain some thermal power available to the load. To prevent the contamination of the gases a filters section is placed outside the electrolyser. In this part of the system the first aim is the obtaining of a very clean and pure hydrogen flow: therefore, a filter to completely remove the presence of oxygen and a filter to remove the humidity in the hydrogen flow are necessary. Very important are also the non-return valves and the anti-flame valves placed after the electrolyser for safety reasons. Last components that are present in this module are manifold and the temperature, pressure, and differential pressure sensors useful to measure and compute all the data necessary in order to control the hydrogen production.

B. Storage module

The second module is the one useful for the storage: therefore, it comprises the compression system, the high-pressure vessel and the pipes, valves, manifolds, and sensors which comply with the pressure and temperature condition of gaseous hydrogen in each section. The gas stream from the production module, which arrives at 30bar, is so compressed in the chosen compressor: as said, in our project situation the compression is made using two air-driven gas boosters placed in series to reach the wanted pressure slightly under 700bar. Before it, a pressure regulator is located in order to obtain a stable pressure at the inlet of first compressor, followed by the sensors useful to control the condition of the hydrogen flow, by a shutoff valve used to intercept the flow in case of malfunction or maintenance, and by control system as pressure switch. The second main component is represented by the pressure vessel. This one is able to store the hydrogen until 700bar so that the energy stored is high if compared with the dimension and weight of tank. In addition, to ensure safety of workers and components, some security valves as safety release valves are placed before and in connection with the high-pressure tank: these are used in case there is the need of discharge the high-pressure fluid in the ambient to prevent damages in the event of over pressurization. It is clear that whatever component placed before the compressor system has to be suited for gaseous hydrogen at least 30bar, while all the elements after the compressor must handle with 700bar hydrogen.

C. Conversion module

It focuses on the energy conversion from hydrogen to electricity and heat in the fuel cell stack. Here the main components are fuel cells, heat exchangers, humidifiers, and power conditioning unit. The first elements in the line of conversion module are the sensors to compute all the data necessary as pressure, temperature, and gas flow rate; and regulators like a pressure reducer to decrease the pressure from the vessel outlet to the inlet of fuel cells. In fact, the pressure at which the FC stack works is equal to 5 bar, while the pressure in the storage system is nearly 700 bar. Subsequently safety release valves and pressure switch are placed, right before the hydrogen humidifier, to control the flux: a right humidification of gases entering the stack is crucial for efficiency and right functioning. Then fuel cells are placed, which are based on the consumption of hydrogen and oxygen flows: while the hydrogen arrives from the system now explained, the oxygen is achieved by the one produced as by product in the electrolyser and, if necessary, by a flow of ambient air that is pumped inside the system after passing a filter section useful to clean it. Finally, the PCU converts the electricity generated with FC in the wanted one to supply the load. In addition to electricity, the heat power is extracted by the fuel cell stack with the use of heat exchangers in order to cool down the component and to increase the total efficiency of the system: this thermal power, along with the one extracted by the electrolyser, will be used by the load, e.g. in residential heating, and in the preheating line of inlet gases. The total system is thus a micro-CHP plant for electricity and heat production with low losses and low potential energy discharged. At the outlet of the stack, a recirculation line connected with the fuel cell inlet is placed in order to make available the excess hydrogen ejected by the anode side and to increase the utilization factor of the fuel.

VI. REGULATION AND DIRECTIVES

Regulations and Standards around the World differs from country to country and often are not in line with the last technologies developed, limiting the possibility of spreading hydrogen. Moreover, some regulations do not consider the final use of the gas. So, it is crucial that governments agree in new Directive and Standards, especially in the following domains:

- ✓ Technology adoption: new hydrogen applications as storage sites and refuelling stations using the latest hydrogen technologies (e.g. storage tanks, nozzle, burners, valves) need harmonised international Standards essential to guarantee consistent operability in the World.
- ✓ Safety: with low-carbon H_2 or hydrogen-based fuels it is still a critical topic. The latest technologies are expected to spread over industry, reaching domestic consumers for mobility and stationary use. So high safety international Standards are fundamental for the public acceptance and harmonization.
- ✓ International trading: in this area the search of a standardised way to compute the carbon footprint of hydrogen production on lifecycle basis is critical, giving the possibility to companies and countries to decide if the carbon footprint of clean hydrogen is acceptable for import it as the same product can be generated by fossil fuel or renewables. This common agreed Standard is essential to avoid impediments in hydrogen trading and to account the emissions of the hydrogen supply chain.

The next step after the development of Standards is the certification and risk assessment. The goal of certifications is to ensure that manufacturers submit to standards adopted internationally giving more certainty to low-carbon hydrogen users. This can help create demand, mobilise investments and stimulate innovation. Europe is working for the realization of international Standards and certifications in order to better regulate and spread hydrogen market: in this direction the European Directive 2014/94/EU about the creation of infrastructures for alternative fuels as natural gas and hydrogen is the foundation to promote the international regulations of new clean alternative fuels [8]. In Italy the hydrogen was considered as a chemical agent produced by fossil fuels until 2018 due to the regulation given by the Ministerial Decree of 31/08/2006, with a lot of restrictions on the production using electrolysers and on storage. The new Ministerial Decree of 23/10/2018 allows, for example, the use of 700 bar pressure hydrogen for use in refuelling stations aligning with the ISO 19880, fundamental Standard for the use of gaseous hydrogen [9]. Nevertheless, Ministerial Decree 23/10/2018 is not enough to reach the proposed goal for hydrogen, so it is crucial the introduction of incentives, the reduction of legal barriers and integration of renewable sources in the energy sector with hydrogen for storage and grid stabilization. Here the main area problems: hydrogen production, stationary storage, hydrogen transport, refuelling stations, hydrogen for mobility on road/railway/sea, hydrogen in pipelines, fuel cell stationary use and grid connection.

Due to hydrogen is an explosive gas, another important Directive involved is the ATEX Directive. The acronym ATEX, abbreviation of French words ATmosphères

EXplosibles, refers to the explosive environments that can be found and from which is important to pay attention for the safety of individuals and regulation of devices. In these terms, European Union (EU) implements two Directives:

- ✓ Directive 2014/34/EU sets the conditions for the design and installation of products and equipment fit for the use in potentially explosive environment in the EU [10];
- ✓ Directive 99/92/CE imposes to all Member States to guarantee the safety and health of workers in possible explosive atmosphere [11].

These Directives impose responsibility to whoever produce, sell, import, or use products and protections in the explosive atmosphere.

The Technical Report ISO/TR 15916 proposes horizontal safety recommendations, factors to be used in risk analysis and possible ignition sources. The TR is not binding but is a good help to the complex subject.

For hydrogen generator (water electrolyser), there is the international standard ISO 22734: “Hydrogen generators using water electrolysis - Industrial, commercial and residential applications”. It describes in detail the requirements for the design, construction, safety and operation of electrolysis plants. It is important to emphasized that the manufacturer of such plants is obliged to carry out an adequate risk assessment (e.g. ISO 12100: “General principles for design - Risk assessment and risk reduction” or IEC 31010:“Risk management — Risk assessment techniques” or EN IEC 60204-1:” Safety of machinery - Electrical equipment of machines - Part 1: General requirements” for example) with the certainty that the mitigation measures taken are enough to reduce the probability and/or the consequences of risk.

For explosion protection, a “classification of area” should be carried out; it means the determination of potential explosion hazard zones based on EN IEC 60079-10-1: “Classification of areas - Explosive gas atmospheres”, and appropriate national standards.

About the project proposed in this Paper, it focuses on the use of hydrogen, that will be the only gas present inside the system with explosive capacity. It is possible to point out what are the areas, categories of product and groups analysed in the paragraph that fit with this gas. In particular:

- ✓ the possible zones for this type of system are generally Zone 0 or Zone 1 or Zone 2 according to the “Classification of areas” (as explained before);
- ✓ the category group of equipment needed is the “II”, because the system is designed to work in surface (not mines). The level of protection is function of the previous “Classification of areas”;
- ✓ the gas group at which hydrogen belong is the IIC, so the most dangerous subdivision of group II, even if also equipment registered as IIB+H2 are correct;
- ✓ the temperature group is the T1 because the autoignition temperature of hydrogen is around 570°C, higher than the T1 group limit 450°C, so all the temperature group classifications are compatible with hydrogen.

Based on the assessment, appropriate prevention protection measures of the occurrence of explosive atmospheres and prevention protection measures of ignition sources (in accordance with the EN IEC 60079 and EN ISO 80079-36 series of standards) must therefore be taken. If necessary, also by means of consequence protection measures (in accordance with CEN TC 305 and ISO 80079 standards). What is required by EN 1127-1: "Explosive Atmospheres - Explosion Protection - Part 1: Basic Principles and Methodology", in general adequately covers the process of risk assessment and analysis and prevention or mitigation measures, as a technical standard it is therefore of primary importance [12].

In conclusion it is very important to produce a Risk assessment of the final system in order to evaluate all the possible risks of ignition can arise during operation. The risk management strategy consists in the recognition and classification of hazards identifying the dangerous scenarios and planning how to manage risks: in the case of hydrogen gaseous system, the hazard starts with gas leakage, gas dispersal, ignition, fire/explosion to arrive until property damage and personal injury. The hazard can be managed in three different ways: eliminating the risk; controlling the risk and mitigating the risk.

In order to avoid the creation of flammable mixtures in the system proposed, it is important to utilize suitable containment both for the hydrogen devices used and for the electrical devices, and to place equipment with appropriate orientation and with right ventilation inside the container. About ventilation, that is considered as a hazard control to reduce the quantity of hydrogen gas (e.g., also useful to pass from zone 1 to zone 2), it is fundamental in a closed system like the one studied to avoid the stall of the gas inside the container.

VII. SCENARIO AND OBTAINED RESULT

In this paragraph the scenario that is possible to obtain when working with design conditions is analysed. Some hypothesis and assumptions are important to be specified in order to make the calculations clear and easier:

- ✓ the system operates at steady-state;
- ✓ the gases are considered as ideal;
- ✓ fast changes in data are not considered so the average values are used for solar irradiance and power demand;
- ✓ heat losses from boundaries are negligible;
- ✓ the BOP consumption is considered equal to about the 5% of the system power output, excluding the PCU with an efficiency of 96%;
- ✓ the preheating line is only fed with the thermal power recovered.

To gain the wanted electric power equal to 15kW from fuel cell stack, it is necessary to have a hydrogen flow of about 12 Nm^3/h. As the electrolyser in our project consumes 4.5 kWh/Nm^3, this reflects in the need of 54kW input. The First Law efficiency of electrolyser (VII.1) can be computed as:

$$\eta_{I,electrolyzer} = \frac{\dot{m}_{H2} * LHV_{H2}}{\dot{W}_{in,el}} = 63.7\ \% \qquad \text{(VII.1)}$$

Where:

- ✓ m_{H2} is the hydrogen flux generated by the electrolyser;
- ✓ LHV_{H2} is the lower heating value of the hydrogen gas;
- ✓ $W_{in,el}$ is the power consumption of the electrolyser represented by the electrical power input.

The next step is represented by the compression, which power consumption is estimated before and equal to about 5.5kW to compress the hydrogen nominal flow up to 690bar. It is so possible the calculation of the net electrical power output from the system called $W_{net,PEM}$ (as reported in VII.2). This value is in function of the stack power output (W_{PEM}), the PCU efficiency (η_{PCU}), and the power consumption of BOP (W_{BOP}) made by pumps, blowers, humidifiers, and fans for ventilation, and compressors

($W_{Compressor}$), so almost all the other components inside of the system that will be powered by the fuel cells.

$$\dot{W}_{net,PEM} = (\dot{W}_{PEM} * \eta_{PCU}) - \dot{W}_{BOP} - \dot{W}_{Compressor} = 8.2\ kW \quad \text{(VII.2)}$$

It results in a value around 8.2kW. We can now compute the First Law efficiency of the PEM system ($\eta_{I,PEM}$), knowing the net power output now calculated ($W_{net,PEM}$) and the product between hydrogen flow (m_{H2}) and lower heating value of the gas (LHV_{H2}) that represents the output energy from the electrolyzer.

$$\eta_{I,PEM} = \frac{\dot{W}_{net,PEM}}{\dot{m}_{H2} * LHV_{H2}} = 23.8\ \% \quad \text{(VII.3)}$$

The PEM efficiency related only to the electricity production is equal to about 23.8%. Moreover, in order to take into account also the heat power recovered by the system, it is possible to compute the First Law efficiency of the so-called micro-CHP (Combined Heat and Power):

$$\eta_{I,CHP} = \frac{\dot{W}_{net,PEM} + \dot{Q}_{HX}}{\dot{m}_{H2} * LHV_{H2}} = 31.1\ \% \quad \text{(VII.4)}$$

Where:

- ✓ Q_{HX} is precisely the thermal power output recovered by the heat exchangers;
- ✓ $W_{net,PEM}$ is the total electric power output;
- ✓ the denominator is the power inlet in the fuel cell stack.

Assuming that the outlet flow of hot water from the fuel cell is able to recover, trough the heat exchangers, around 2.5kW, the cogenerated PEMFC system First Law efficiency will be equal to about 31.1%. The value of thermal power recovered is assumed knowing that the outlet hot water from fuel cell stack is around 9 times the inlet hydrogen flow, so nearly 9kg/s, with 80-90°C temperature. As the water is cooled down until ambient temperature in the heat exchangers, it is possible to obtain a 65°C average temperature difference [13]. So the thermal power is computed:

$$Q_{HX} = \dot{m}_{H2O} * c_{P,H2O} * \Delta T_{H2O} = 2.5\ kW \quad \text{(VII.5)}$$

Where:

- ✓ m_{H2O} is the outlet hot water mass flow;
- ✓ $c_{P,H2O}$ is the water specific heat;
- ✓ ΔT_{H2O} is the water temperature difference.

The total First Law efficiency of the system is so computed knowing the value just calculated of the electrolyser efficiency ($\eta_{I,electrolyzer}$) and the PEM cogenerated efficiency ($\eta_{I,CHP}$):

$$\eta_{I,total} = \eta_{I,electrolyzer} * \eta_{I,CHP} = 19.8\ \% \quad \text{(VII.6)}$$

The result is 19.8 %: this value means that, starting from the electrical power input at the electrolyser, it is possible to convert and store it in high pressure vessel as hydrogen for long time and, finally, about one fifth of it is available as electricity and heat when needed without direct pollution emission.

VIII. CONCLUSION

This project is focalized on the study of a small cogenerative system where electricity and heat are provided by a fuel cell stack whose input hydrogen, stored in high pressure vessel, is firstly produced by an electrolyser powered by renewables in the optimal case. The performances of the whole system are, as seen, function of several elements so the efficiency can vary a lot. In the ideal situation the system is intended to work as a storage technology for the renewables power plants, also called Power-to-gas system, in order to convert the additional power produced, when available, in hydrogen gas storable for long time, and use it, when necessary, to cover peak demand situation or when the renewables cannot produce enough power for the load without direct pollution emission. As demonstrated, starting from an inlet power, at electrolyser level, equal to 54 kW, it is possible to run a fuel cell stack of 15 kW design output, obtaining around 8.2 kW of total power output in the "only-electricity" case and about 10.7 kW in the CHP case. Thus, the efficiency between inlet and outlet is quite low (19.8 %), but it is important to remember that this power is only produced with the wasted one by renewable power plants running in a situation where the power consumption of the load is lower than its production.

Figure 4 shows the different storage technologies that are nowadays available to store energy. It is clearly visible how hydrogen, as gasoline but without carbon emission, represents the technology with the highest specific energy (Wh/kg) compared to capacitors and batteries. Moreover, it has also a very competitive specific power (W/kg), second only to metal oxide capacitors. This two information give us the certainty that hydrogen, as explained, is a very good energy vector both for the instantaneous power and for the long-term energy services [14]. The main issues are given by the very high cost to produce hydrogen and to create all related systems to use it and by the difficult in transportation as it needs to be liquified or compressed until high pressure to be economically sustainable.

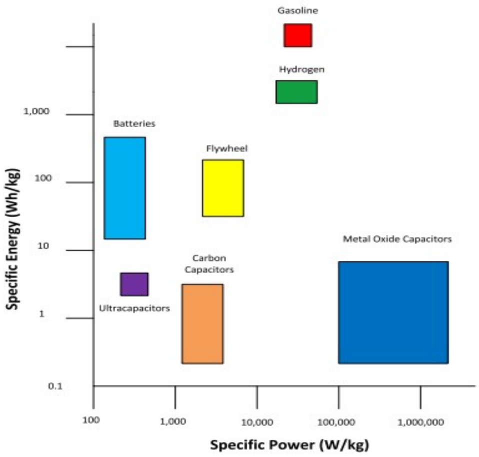


Figure 4: Comparison between energy storage technologies

Comparing, in Figure 5, hydrogen with the currently most widespread technology for energy storage, batteries, we can figure out a very important aspect. Batteries are very good in term of cost and efficiency for small and medium applications, but an increasing in the storage capacity leads to very high system cost. On the contrary, hydrogen system cost is very high due to the elevated price of its components even when talking about small storage capacities, but the cost increases slowly rising the kWh available by the storing system.

This trend leads to a size where the hydrogen system become more economically feasible than the batteries, around 4kg of hydrogen capacity or 100kWh of storage [15]. Therefore, hydrogen storage systems are better in the mid and long-term storage when the storable energy capacity need to be high enough to store over 12 hours of autonomy. This is considered the changeover point to the choice of hydrogen storage systems over batteries.

In conclusion, another important issue is related to the Standardization. It is crucial the introduction of incentives, the reduction of legal barriers and integration of renewable sources in the energy sector with hydrogen for storage and grid stabilization without forgetting that hydrogen is an explosive gas

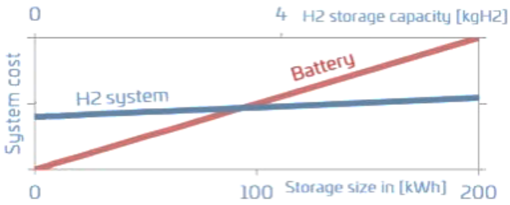


Figure 5: Hydrogen system vs batteries

Ultimately, the biggest challenge associated with scaling up hydrogen production remains "regulatory barriers".

IX. REFERENCES

[1] IEA (2021), Data and Statistics - World, IEA, Paris, Data & Statistics – IEA

[2] NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published December 2021, retrieved on January 7, 2022, https://www.ncdc.noaa.gov/cag/

[3] J.D. Holladay, J. Hu, D.L. King, Y. Wang, An overview of hydrogen production technologies, Catalysis Today, Volume 139, Issue 4, 2009, Pages 244-260, https://www.sciencedirect.com/science/article/pii/S0920586108004100

[4] Ibrahim Dincer, Green methods for hydrogen production, International Journal of Hydrogen Energy, Volume 37, Issue 2, 2012, Pages 1954-1971, https://www.sciencedirect.com/science/article/pii/S0360319911019823

[5] V. Malik, S. Srivastava, Comparative study and analysis between Solid Oxide Fuel Cell (SOFC) and Proton Exchange Membrane fuel cell (PEMFC) – A review, Materials Today: Proceedings, Volume 47, Part 10, 2021, Pages 2270-2275, https://www.sciencedirect.com/science/article/pii/S2214785321031102

[6] S. Shiva Kumar, V. Himabindu, Hydrogen production by PEM water electrolysis – A review, Materials Science for Energy Technologies, Volume 2, Issue 3, 2019, Pages 442-454, https://www.sciencedirect.com/science/article/pii/S2589299119300035

[7] Hydrogen and Fuel Cell Technologies Office | Department of Energy

[8] IEA (2021), Global Hydrogen Review 2021, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2021

[9] 2IT, Piano nazionale di sviluppo - Mobilità idrogeno in Italia, November 2019

[10] ATEX 2014-34-EU Guidelines, 3rd Edition May 2020

[11] DIRECTIVE 1999/92/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 1999 on minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres (15th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC)

[12] International Standard ISO 22734 09-2019, IEC 60079, Hydrogen generator using water electrolysis – Industrial, commercial, and residential application

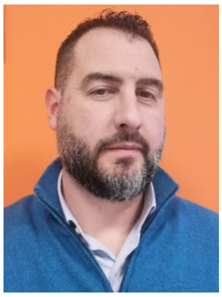
[13] Juan E. Tibaquirá, Kiril D. Hristovski, Paul Westerhoff, Jonathan D. Posner, Recovery and quality of water produced by commercial fuel cells, International Journal of Hydrogen Energy, Volume 36, Issue 6, 2011, Pages 4022-4028, https://www.sciencedirect.com/science/article/pii/S0360319910024146

[14] National Renewable Energy Laboratory. http://www.nrel.gov

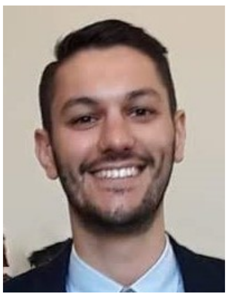
[15] R.S. Faranda, K. Fumagalli, M. Bielli - Lithium-ion batteries for Explosive Atmosphere, PCIC EUR19_32, Paris

X. VITA

Roberto Sebastiano Faranda received the Ph.D. degree in electrical engineering from the Politecnico di Milano, Milano, Italy, in 1998. He is currently Full Professor with the Department of Energy, Politecnico di Milano. His research areas include power electronics, power system harmonics, power quality, power system analysis, smart grids, Ex environment and distributed generation. Dr. Faranda is a member of the Italian Standard Authority; the Italian Electrical, Electronic, Automation, Information, and Telecommunications Federation; and the Italian National Research Council group of Electrical Power Systems. He has authored more than 150 papers. roberto.faranda@polimi.it



Kim Fumagalli graduated in Electrical Engineering from the University of Politecnico di Milano in 2005. He obtained the Ph.D. degree in Electrical Engineering at Politecnico di Milano, Milan, Italy, in 2009. His research areas include LED Source and LED Lighting System, Electrical and Lighting systems, batteries, PV panels for Explosive Atmosphere, Ex Products Certification and Testing. He is a collaborator of the Department of Energy, Politecnico di Milano. He is a member of several IEC Work Group. He has received IECEx Certificate Personnel Competence. He is a member of the PCIC Europe committee and holds the position as Assistant Technical Secretary. He has authored several papers. kim.fumagalli@polimi.it



Cosimo Menici, graduated from Politecnico di Milano University in 2022 with a MSc degree in Energy Engineering – Green Power Systems. During the stage for master thesis, he focused on hydrogen production and use in potentially explosive atmosphere. Now he works as project engineer for energy efficiency sector in Piemme Energia, Milan, studying and realizing solutions to decrease energy consumption and pollution of customers. cosimo.menici@mail.polimi.it