



UNIVERSITÀ POLITECNICA DELLE MARCHE

ENGINEERING FACULTY

Master Degree in Environmental Engineering

**HYDROGEN PRODUCTION FROM RENEWABLE ENERGY:
MARKET INTELLIGENCE OF USES AS TECHNICAL GAS**

AUTOR:
LORETA BRUNI

SUPERVISOR:
PROF. ENG. GABRIELE COMODI

ASSISTANT SUPERVISOR:
PROF. ENG. GIORGIO PASSERINI
EXTERNAL ASSISTANT SUPERVISOR:
ENG. MAURO MORONI

A C C A D E M I C Y E A R 2 0 1 9 / 2 0 2 0

*A MIA MADRE E A MIO PADRE,
I PILASTRI DELLA MIA VITA.*

ACKNOWLEDGEMENTS

First of all, I would like to thank Professor Eng. Gabriele Comodi for accepting the position of supervisor for my thesis despite the fact that I was not one of his students and for giving me the opportunity to study the subject of renewable energy. I would like to thank Eng. Mauro Moroni for giving me the opportunity to live this experience within his company Moroni & Partners. A special thanks goes to my company tutor Eng. Remo Fagnani because, despite his great responsibilities and numerous commitments in the company, he has always found the time and patience to listen to me, to advise me and to develop my thesis project in the best possible way.

ABSTRACT

Hydrogen is abundant, uniformly distributed throughout the Earth's surface and its oxidation product (water) is environmentally benign. Owing to these features, it is considered the *ideal energy carrier*.

It is a reality that has been spreading in recent years, but it has been talked about for decades. The problem is that the name Hydrogen has been combined with a negative meaning following two serious episodes, one in 1936 concerning the German zeppelin LZ 129 Hindenburg and the other is the hydrogen bomb. It must be treated as safely as all other fuels, but it is no longer dangerous, for example, than oil.

Another reason why it didn't spread before was related to costs, which were too high and made oil more and more competitive because it was cheaper.

But today, hydrogen systems are becoming more efficient and less expensive.

The emergence of new technologies concurs to make it a vital resource for the economy of the future by fulfilling part of *Julies Verne's* prophecy.

This thesis work will explain the characteristics, the production methods, the storage of both hydrogen and oxygen, and will be focused on the production of green hydrogen. A study was carried out on a pilot plant for the production of hydrogen and oxygen powered by solar energy. A market analysis has been conducted in the Marche region to identify the ideal location of the future plant.

"Hydrogen offers us a way to live a greener, fairer and more prosperous world."

CONTENTS

CHAPTER 1	1
1 INTRODUCTION	1
CHAPTER 2	4
2 HYDROGEN	4
2.1 THE DISCOVERY OF HYDROGEN	4
2.2 CHEMICAL AND PHYSICAL CHARACTERISTICS OF HYDROGEN	6
2.3 PRODUCTION TECHNOLOGIES.....	9
2.3.1 STEAM REFORMING PROCESS	11
2.3.2 PARTIAL OXIDATION OF HYDROCARBONS	12
2.3.3 GASIFICATION OF COAL.....	13
2.3.4 GASIFICATION AND PYROLYSIS OF BIOMASS	15
2.3.5 ELECTROLYSIS OF WATER	16
2.3.6 COST OF PRODUCTION.....	25
2.4 STORAGE OF HYDROGEN	26
2.4.1 STORAGE AS COMPRESSED GAS	27
2.4.2 STORAGE AD LIQUEFIED HYDROGEN	28
2.4.3 METAL HYDRIDE.....	29
2.4.4 NANOSTRUCTURES OF CARBON.....	31
2.5 TRANSPORT OF HYDROGEN.....	32
2.5.1 TRANSPORT OF COMPRESSED HYDROGEN	32
2.5.2 BLENDING WITH NATURAL GAS	38
2.5.3 TRANSPORT OF LIQUEFIED HYDROGEN	41
2.5.4 COMPARISON BETWEEN DIFFERENT MODE OF TRANSPORT AND RELATIVE COST	42
2.6 APPLICATIONS OF HYDROGEN	45
CHAPTER 3	47
3 OXYGEN	47
3.1 THE DISCOVERY OF OXYGEN	47
3.2 CHEMICAL AND PHYSICAL CHARACTERISTICS OF OXYGEN	47
3.3 PRODUCTION TECHNOLOGIES.....	50
3.3.1 FRACTIONAL DISTILLATION OF AIR AT LOW TEMPERATURE	50
3.3.2 SEPARATION FROM AIR BY ADSORPTION	52
3.3.3 SEPARATION FROM AIR BY MEMBRANES.....	52
3.3.4 DECOMPOSITION OF OXIDES AND SALTS	53
3.4 STORAGE AND TRANSPORT OF OXYGEN	53
3.5 APPLICATION OF OXYGEN	54
3.6 REGULATION FOR THE USE OF TECHNICAL GASES OXYGEN AND HYDROGEN	56
CHAPTER 4	57
4 MARKET ANALYSIS.....	57
CHAPTER 5	62
5 HYDROGEN AND OXYGEN POWER PLANT.....	62
5.1 INTERNATIONAL STANDARDS.....	64

5.2	SAFETY REGULATIONS	65
5.3	PERMITTING FOR H ₂ PRODUCTION AND STORAGE	66
5.3.1	LAND USE PLAN.....	68
5.3.2	PERMITTING REQUIREMENTS	68
5.4	GRID CONNECTION OF HYDROGEN PTG PLANT	69
5.5	PERMITTING PROCEDURES FOR H ₂ INJECTION INTO THE GAS GRID.....	69
5.6	PERMITTING PROCEDURES IN TRANSPORTATION OF H ₂	70
5.7	ANALYSIS OF WATER AVAILABILITY	71
5.7.1	REGULATORY FRAMEWORK FOR WATER SUPPLYING	71
5.7.2	ANCONA PROVINCE WATER SUPPLY REGULATION.....	71
CHAPTER 6	72
6	RENEWABLE ENERGIES	72
6.1	EVOLUTION OF RENEWABLE ENERGIES AND THEIR COSTS.....	74
6.2	EVOLUTION OF THE COST OF GREEN HYDROGEN	76
6.3	SOLAR ENERGY.....	78
6.3.1	PV POWER PLANT COMPONENTS	79
6.4	CASE OF STUDY: PV POWER PLANT	81
6.4.1	RADIATION AND ENERGY PRODUCIBILITY	85
6.5	BUSINESS PLAN	86
6.6	SCENARIO 1	86
6.6.1	CAPEX SCENARIO 1.....	87
6.6.2	OPEX SCENARIO 1.....	87
6.6.3	ECONOMIC RESULTS SCENARIO 1	89
6.7	SCENARIO 2	98
6.7.1	CAPEX SCENARIO 2.....	99
6.7.2	OPEX SCENARIO 2.....	99
6.7.3	ECONOMIC RESULTS SCENARIO 2	100
6.8	SCENARIO 3	105
6.8.1	CAPEX SCENARIO 3.....	105
6.8.2	OPEX SCENARIO 3.....	105
6.8.3	ECONOMIC RESULTS SCENARIO 3.....	106
CONCLUSION	111

LIST OF FIGURE

FIGURE 1 - OVERSHOOT DAY	2
FIGURE 2 - ISOTOPES OF HYDROGEN	6
FIGURE 3- DIAGRAM OF HYDROGEN PRODUCTION FROM DIFFERENT SOURCES	9
FIGURE 4 - THE FEEDSTOCK USED IN THE CURRENT GLOBAL PRODUCTION OF HYDROGEN.....	10
FIGURE 5 - STEAM REFORMING PROCESS	12
FIGURE 6 - LAYOUT OF GASIFICATION PLANT.....	13
FIGURE 7 - ELECTROLYTIC CELL.....	17
FIGURE 8 - LAYOUT OF ALKALINE ELECTROLYSER.....	18
FIGURE 9 - LAYOUT OF PEM ELECTROLYSER	19
FIGURE 10 - LAYOUT OF SOEC ELECTROLYSER.....	19
FIGURE 11 - DEVELOPMENT OF ELECTROLYSER CAPACITY ADDITIONS FOR ENERGY PURPOSES AND THEIR AVERAGE	21
FIGURE 12 - PILOT FACILITY IN SICILY	24
FIGURE 13 - PILOT FACILITY IN PUGLIA	24
FIGURE 14 - CHAIN OF COLLECTION, TRANSMISSION, DISTRIBUTION OF HYDROGEN.....	26
FIGURE 15 - COMPRESSED HYDROGEN GAS STORAGE TANK.....	27
FIGURE 16 - LIQUEFIED HYDROGEN TANK.....	28
FIGURE 17 - HYDROGEN CHARGING AND DISCHARGING PROCESS USING METAL HYDRIDE STORAGE	30
FIGURE 18 – NANOTUBE OF CARBON	31
FIGURE 19 - TRUCK FOR COMPRESSED HYDROGEN	32
FIGURE 20 - PIPELINES IN NORTH EUROPE.....	37
FIGURE 21 - PIPELINES IN THE USA	37
FIGURE 22 - CO ₂ EMISSIONS VS VOLUMETRIC CONCENTRATION H ₂	38
FIGURE 23 - TRUCK FOR LIQUEFIED HYDROGEN	41
FIGURE 24 - LNG SHIP	42
FIGURE 25 - AREAS OF APPLICATION	45
FIGURE 26 - ISOTOPES OF OXYGEN	48
FIGURE 27 – CRYOGENIC DISTILLATION	51
FIGURE 28 – ADSORPTION PROCESS	52
FIGURE 29 - USE OF HYDROGEN IN REFINING PROCESS.....	59
FIGURE 30 - LAYOUT MODULES.....	63
FIGURE 31 - RENEWABLE ENERGIES	72
FIGURE 32 - EVOLUTION OF RENEWABLE ENERGIES	74
FIGURE 33 – INCREASING OF SOLAR PV TECHNOLOGIES	75
FIGURE 34 - FALLING OF THE COST FOR SOLAR AND WIND ENERGY	76
FIGURE 35 - HYDROGEN PRODUCTION COSTS FROM SOLAR AND WIND VS. FOSSIL FUELS	77
FIGURE 36 - COMPONENTS OF PV POWER PLANTS	80
FIGURE 37 - LOCALIZATION OF THE PV POWER PLANT.....	81
FIGURE 38 - LAYOUT OF THE PV POWER PLANT	82
FIGURE 39 - CUMULATIVE CASH FLOW SCENARIO 1	92
FIGURE 40 - CUMULATIVE CASH FLOW WITH AN INTEREST RATE OF 5% SCENARIO 1	94
FIGURE 41 - CUMULATED CASH FLOW IDEAL SCENARIO	97
FIGURE 42 - DISCOUNTED CASH FLOW IDEAL SCENARIO	97
FIGURE 43 - RESULT OF PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM.....	98
FIGURE 44 - CUMULATIVE CASH FLOW SCENARIO 2	104
FIGURE 45 - DISCOUNTED CASH FLOW SCENARIO 2	104
FIGURE 46 - CUMULATED CASH FLOW SCENARIO 3.....	109
FIGURE 47 - DISCOUNTED CUMULATED CASH FLOW SCENARIO 3	109

LIST OF TABLE

TABLE 1 - PHYSICAL - CHEMICAL PROPERTIES OF HYDROGEN	8
TABLE 2 - COMPARISON BETWEEN THREE DIFFERENT OF ELECTROLYSERS	20
TABLE 3 - PURITY OF HYDROGEN	23
TABLE 4 - COMPARISON OF DIFFERENT HYDROGEN PRODUCTION METHODS.....	25
TABLE 5 - COST OF COMPRESSED AND LIQUID HYDROGEN STORAGE METHODS	29
TABLE 6 - CHARACTERISTICS OF PIPES IN THE WORLD	35
TABLE 7 - GAS QUALITY PARAMETERS FROM MINISTERIAL DECREE 18 MAY 201.....	40
TABLE 8 - COMPARISON OF DIFFERENT TRANSPORT METHOD	43
TABLE 9 - TRANSPORT COST OF HYDROGEN BY RAIL	44
TABLE 10 – PHYSICAL - CHEMICAL PROPERTIES OF OXYGEN	49
TABLE 11 - OXYGEN PARAMETER.....	56
TABLE 12 - OXYGEN AND HYDROGEN PARAMETERS IN FOOD FIELD.....	56
TABLE 13 - HYDROGEN USERS IN MARCHE REGION	58
TABLE 14 - OXYGEN USERS IN MARCHE REGION	60
TABLE 15 - OXYGEN USERS IN NORTH ABRUZZO REGION.....	61
TABLE 16 - RENEWABLE ENERGIES AND THEIR USE.....	73
TABLE 17 - CHARACTERISTICS OF PV MODULES	83
TABLE 18 - INVERTER CHARACTERISTICS.....	84
TABLE 19- CAPEX H ₂ -O ₂ POWER PLANT	87
TABLE 20 - PRICE OF ELECTRICITY CAPTURED BY PV	88
TABLE 21 - OPEX H ₂ -O ₂ POWER PLANT	88
TABLE 22 – REVENUES H ₂ -O ₂	89
TABLE 23 - TOTAL REVENUES	89
TABLE 24 - EBITDA.....	90
TABLE 25 - NET CASH FLOW	91
TABLE 26 - CUMULATED CASH FLOW.....	92
TABLE 27 - DISCOUNTED CASH FLOW	94
TABLE 28 – OPEX AND EBITDA.....	95
TABLE 29 - CASH FLOW	96
TABLE 30 – CAPEX SCENARIO 2.....	99
TABLE 31 -TOTAL OPEX SCENARIO 2.....	100
TABLE 32 - REVENUES	101
TABLE 33 - EBIDTA.....	102
TABLE 34 - CASH FLOW	103
TABLE 35 - CAPEX H ₂ -O ₂ POWER PLANT	105
TABLE 36 - OPEX SCENARIO 3	106
TABLE 37 - REVENUES H ₂ - O ₂	106
TABLE 38 – TOTAL REVENUES.....	107
TABLE 39 - ECONOMIC RESULTS.....	108

"Without coal there would be no machinery, and without machinery there would be no railways, no locomotives, no factories, nothing that modern civilization needs!"

"But will we find something else?" asked Pencroft. "Can you tell us captain?"

"More or less, dear friend."

"And what will they burn instead of coal?"

"Water," Harding replied.

"Water!" Pencroft exclaimed, "water as fuel for locomotives and engines! Water to heat the water "

"Yes, but water broken down into its primitive elements," replied Cyrus Harding. "Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable. Water will be coal for the future".

Jules Verne, "The mysterious island" 1874.

CHAPTER 1

1 INTRODUCTION

"A planet is not enough".

This is what the Global Footprint Network, an international association for sustainability that deals with environmental accounting by calculating the ecological footprint to determine *the Earth Overshoot Day*, literally "the day of overcoming", reports.

The day of overfishing marks the date when man's consumption of resources exceeds what Earth's ecosystems are able to regenerate for that year. Over the past 20 years, the day of overfishing has moved up to three months ahead of the calendar to fall on July 29 in 2019.

Never before July 29, 2019 had humanity exhausted its annual natural capital so soon. Given the rate at which we have used up the renewable resources that Earth is able to regenerate in 365 days, it is as if we were using the resources of 1,75 Earth planets.

In other words, man is currently using natural resources at a rate of 1,75 times faster than the regeneration capacity of ecosystems. Overshoot is possible because we are depleting our natural capital, which compromises humanity's future resource security.

Although the amount of CO₂ in the atmosphere has reached record peaks and the animal species are dying out at a speed never seen before, we are still in time to try to avoid the environmental collapse. Moving the date of the Overshoot day by five days per year would allow humanity to achieve balance with the resources produced annually by the planet before 2050.

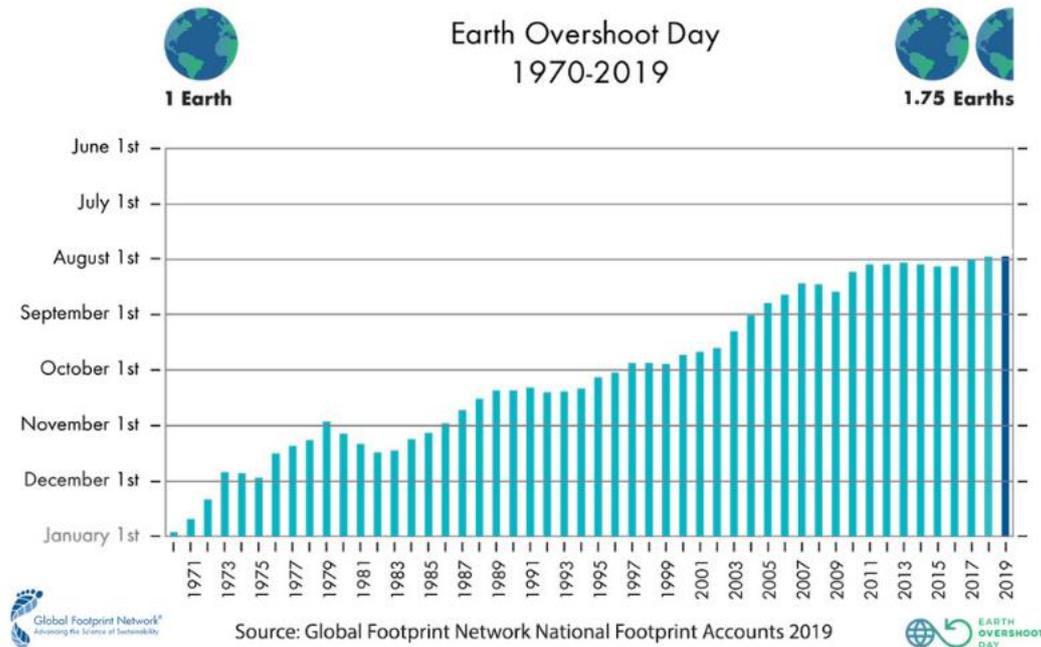


Figure 1 - Overshoot Day

Today's society is facing a crossroads because, on the one hand, there is the need to find and secure energy resources to support growth and development; but on the other, there is the need to mitigate and reduce climate change, ensuring the protection of the environment and the ecosystem for the benefit of present and future generations.

Climate change related to the use of fossil energy sources is the main subject of scientific studies that for years are requiring a need for action by the entire world population; the IEA, 'International Energy Agency', has confirmed that the increasing increase in emissions is not in line with what should be done in terms of global sustainability. It is therefore necessary to limit to a minimum the use of non-renewable energy sources as expensive and polluting for the environment, in favour of renewable energy such as solar, wind and water.

Today, a highly discussed topic is the use of renewable energy sources; it is a consolidated reality and their use for energy production is constantly increasing. This is made possible not only by the continuous technological development, but above all because the Member States have attributed these sources an increasingly strategic role in energy policy choices, both in an effort to reduce

economic and political dependence on the countries supplying fossil fuels, and to cope with their depletion and various environmental emergencies.

Cost reductions in renewable energies and advances in digital technologies are opening up huge opportunities for *energy transitions*. Wind and solar photovoltaic energy provide more than half of the additional electricity generation to 2040 in the scenario of declared policies and almost all growth in the scenario of sustainable development.

The last decade has seen a strong growth in the use of renewable energy technologies, with the energy sector at the forefront thanks to the strong cost reductions for solar photovoltaic and wind energy.

One of the limitations that however affects solar and wind systems is the fact that their operation is linked to the availability of wind or solar radiation; but one of the possible ways of overcoming this disadvantage is through the adoption of mechanisms to allow the storage of energy produced during periods when systems can work properly, and then make it available in those where there is no possibility of exercise.

One of the most promising prospects that has been much discussed in recent years is the use of energy from renewable sources for the production of hydrogen, an ideal energy carrier that can be obtained from at least five renewable and clean sources: hydroelectric, photovoltaic, solar thermal high temperature, geothermal and wind and its production can be organized anywhere.

Considering the problem of continuously increasing of energy demand, a solution to this problem will be the use of renewable sources and new fuels so the possibility of producing energy with zero emissions has increased interest in this hydrogen technology.

Hydrogen is not available in nature in the simple state, but it is necessary to produce it with a variable energy expenditure depending on the type of process.

CHAPTER 2

2 HYDROGEN

Hydrogen is not an "*energy source*", which means that it is not a primary energy (such as natural gas or crude oil) that exists free in nature, but instead it is an "*energy carrier*", a secondary form of energy that must be produced, just as electricity does not exist in the free state in either form. Hydrogen can be generated from many primary sources; it can do the same things as other forms of energy but without polluting.

Hydrogen, an invisible gas, colourless and odourless, is the most abundant element in our universe. It is the fuel of stars and galaxies. It is essential in countless chemical and biological processes due to its extremely reactive characteristics. It has a further significant aspect: as a raw material it can be used in countless uses.

Its use does not involve environmental impact or minimizes it: if burned with pure oxygen it gives water as a single product; if instead it is burned in air oxides of nitrogen are also generated because of the presence of oxygen and nitrogen in air. We can say that hydrogen is a form of energy of high quality, ecological, versatile and universal.

2.1 THE DISCOVERY OF HYDROGEN

The nature of hydrogen began to emerge in the 16th century when Paracelsus first described a gaseous product that formed when iron was dissolved in sulfuric acid. The scientist did not realize that the gas produced was a new chemical element; he described it as "*air bursting like wind*".

Herman Boerhavave, a Dutch physicist and naturalist, was the first to suspect that there was an element in the air that could contribute to life and that was the key to breathing and combustion; in 1732 he wrote: "*We don't know much about it now, but chemists will find out in the future what it is, how it works and what it does. Lucky who finds out*".

In 1671, Robert Boyle, an Irish chemist, physicist and naturalist, produced pure hydrogen again and published the article "New experiments touching the relation

between flame and air" in which he described the reaction between iron filings and diluted acids, which leads to the formation of H₂ gas, which he called "*inflammable solution of Mars*".

Henry Cavendish, an English scientist, was the first to discover and describe the qualities of hydrogen, but without naming it as an element but influenced by the phlogiston theory defined it as "*flammable air*". In 1766, Cavendish presented his first scientific paper in which he stated that he had discovered that the gas was extraordinarily light, with a density equal to a fourteenth of that of the air itself and showed that by mixing flammable air (hydrogen) with air and setting fire to the mixture with an electric spark, it produced water and a remnant of air.

Antoine-Laurent de Lavoisier, a French chemist who learned of Cavendish's work, refuted the theory of phlogiston and by combining hydrogen and oxygen he obtained 45 grams of water. In 1785, Lavoisier conducted some definitive experiments, and demonstrated that hydrogen and oxygen constituted the basic elements of water; in fact, he named it "hydrogenium", that is to say "*water generator*".

In 1793, large-scale hydrogen production was planned; Guyton de Norveau, a French chemist, suggested to the army the use of hydrogen-filled brake balloons as observation platforms. The first hydrogen generator was built in early 1794 at Maubeuge.

At the beginning of the 19th century, hydrogen was used in the heating and lighting of houses, hotels and apartments and in the provision of street lighting; but often the mixture was not just hydrogen but a mixture of gases containing carbon; this confusion was due to the fact that all these gases were lighter than air.

In 1931, Harold Clayton Urey discovered a hydrogen isotope, atomic weight 2, called deuterium. The hydrogen isotope of atomic mass 3, called tritium, was produced in 1934 by Rutherford, along with Oliphant and Harteck, bombarding deuterium with other deuterium nuclei. Rutherford was not able to isolate the tritium, but Luis Álvarez was able to, who correctly deduced that the substance was radioactive. The isotope commonly referred to as hydrogen is protium due to its abundance (about 99,98% of total hydrogen). Its most common presence on Earth is in the molecule of water.

2.2 CHEMICAL AND PHYSICAL CHARACTERISTICS OF HYDROGEN

Hydrogen, symbol H, is the first element in the periodic table of elements, belonging to the group IA of non-metals. Its atomic number is one and its electronic configuration is $1s^1$, this means that the hydrogen atom has only one electron which is placed on the lowest energy orbital (1s).

It is the lightest of the elements being made up of one proton and one electron.

Hydrogen has a density of 0,08988 g/L, making it less dense than air. It has two distinct oxidation states, (+1, -1), which make it able to act as both an oxidizing and a reducing agent.

Natural hydrogen actually presents itself as the mixture of two isotopes, that is, species that differ only by the different number of neutrons present in the nucleus: the protium, which has a nucleus without neutrons, and the deuterium, which has a nucleus with a proton and a neutron. Deuterium is only present in the natural mixture for 0,02%. A third isotope, tritium, with a nucleus with one proton and two neutrons, is produced in nuclear interactions.

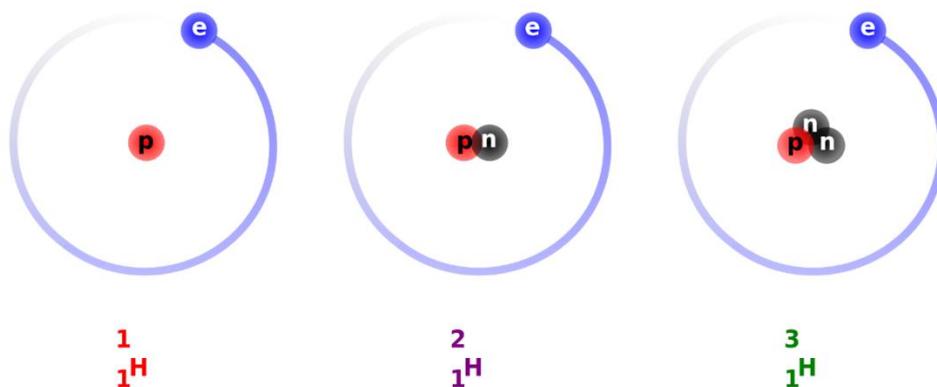


Figure 2 - Isotopes of hydrogen

According to the New Columbia Encyclopedia, hydrogen accounts for 75% of the mass of the universe and 90% of its molecules.

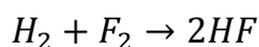
Elemental hydrogen on our planet is very rare; because the earth's gravitational attraction, less than that of stars and large planets, is insufficient to retain very light molecules such as those of hydrogen (its density is 14,4 times lower than that of air).

It is found free in volcanic emanations, in oil sources, in fumaroles and in the atmosphere at a height of over one hundred kilometres. Instead in the combined state it is very abundant; in fact, together with the oxygen we find it in the water of which it constitutes 11,2% in weight; combined with carbon, oxygen and some other elements it is one of the main constituents of the plant and animal world, the human organism contains about 10% of its weight.

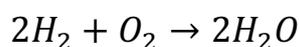
In the field of organic chemistry, millions of compounds containing hydrogen are known, ranging from the simplest of hydrocarbons, methane, to the carbohydrate proteins with a huge number of hydrogen atoms.

Hydrogen, therefore, forms compounds with all known elements except noble gases. Hydrogen has an electronegativity of 2,2 on the Pauling scale, so it reacts with both metals and non-metals. It forms numerous compounds with carbon, called organic compounds, such as hydrocarbon fuels methane (CH₄), ethane (C₂H₆), propane (C₃H₈), butane (C₄H₁₀) and so on.

The hydrogen H₂ molecule has a high dissociation energy value, about 434 kJ/mol, this corresponds to a high activation energy value. At room temperature, it reacts spontaneously and explosively only with fluorine, producing hydrofluoric acid:



At room temperature, hydrogen is chemically poorly reactive due to the high stability of the H₂ molecules that make it up. Lighted to the air, it burns with light blue flame and strongly calorific, reacting with oxygen (O) to form water:



Its reactivity is much greater when it is in the atomic state; some metals (such as platinum and palladium) have the property of absorbing molecular hydrogen, favouring its dissociation into atomic hydrogen and for this reason they are used as catalysts in the reactions in which hydrogen intervenes.

Hydrogen has lowest atomic weight of any substance and therefore has very low density both as a gas and a liquid. Hydrogen has the second lowest boiling points and melting points of all other substances, second only to helium.

The main characteristics of hydrogen are shown in the Table 1.

Table 1 - Physical - Chemical properties of hydrogen

PHYSICAL – CHEMICAL PROPERTIES OF HYDROGEN		
Property	Unit of measure	Value
Molecular weight	g/mol	1,00794
Atomic radius	pm	53
Covalent radius	pm	31±5
Van der Waals radius	pm	120
Density of gas at 0°C and 1 atm	kg/m ³	0,08987
Density of solid at -259°C	kg/m ³	858
Density of liquid at -253°C	kg/m ³	708
Melting temperature	°C	-259,20
Boiling temperature at 1 atm	°C	-253
Critical temperature	°C	-240
Critical pressure	atm	12,80
Critical density	kg/m ³	31,20
Heat of fusion at -259°C	kJ/kg	58
Heat of vaporization at -253°C	kJ/kg	447
Thermal conductivity at 25°C	kJ/(kg°C)	0,019
Viscosity at 25°C	Centipoise	0,00892
Heat capacity (Cp) of gas at 25°C	kJ/(kg°C)	14.3
Heat capacity (Cp) of liquid at -256°C	kJ/(kg°C)	8,10
Heat capacity (Cp) of solid at -259,8°C	kJ/(kg°C)	2,63
Diffusion coefficient	cm ² /s	0,61

Unlike fossil fuels, hydrogen does not generate dangerous by-products during combustion. When hydrogen is combined with oxygen in a fuel cell, only energy and clean water are produced.

Hydrogen is non-toxic but can act as a simple asphyxiant by displacing the oxygen in the air.

2.3 PRODUCTION TECHNOLOGIES

“Hydrogen can be compared to a car's gears. Gears do not in themselves generate energy, but manage to convert the energy available in the engine into useful work ”.

As already mentioned in the previous chapters, hydrogen is an *energy carrier* and can be obtained from different forms of energy from both non-renewable energy sources like natural gas, coal, petroleum, and nuclear as well as from renewable energy sources like wind, solar, hydro, geothermal, algae, and biomass alcohols; using different technologies such as:

- Steam reforming of natural gas;
- Partial oxidation of hydrocarbons;
- Gasification of coal;
- Gasification and Pyrolysis of biomass;
- Electrolysis of water.

The first three technologies are obtained from fossil fuels and the other two from renewable energies.

A diagram of the hydrogen production process is shown in the Figure 3.

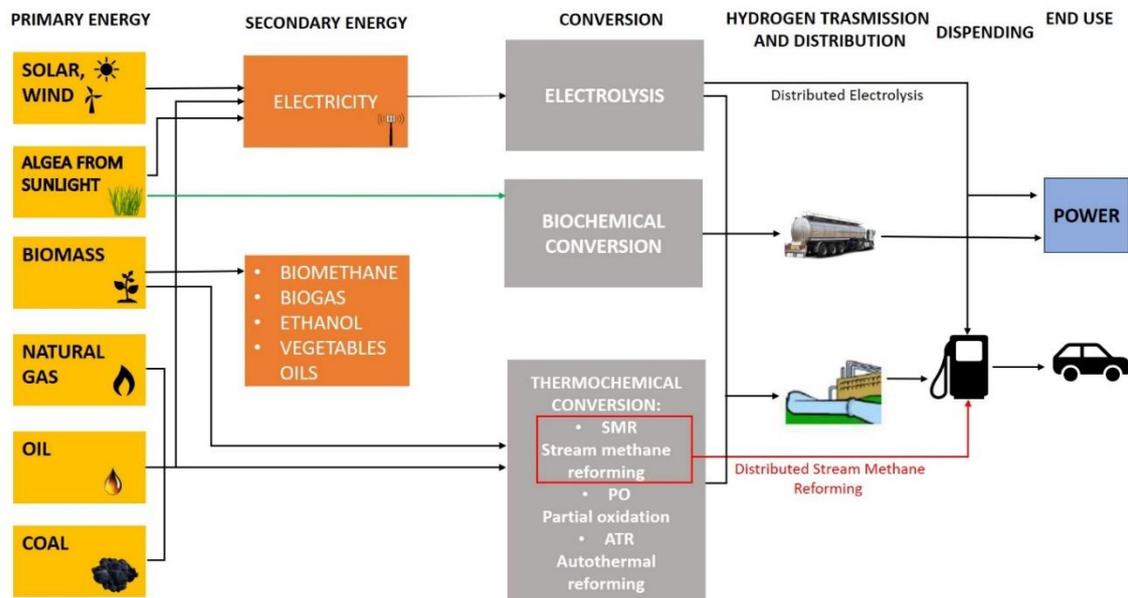


Figure 3- Diagram of hydrogen production from different sources

Nowadays the commercial hydrogen production is made from fossil fuel feedstock as shown in the Figure 4. It can be seen from the figure that 48% of the world's hydrogen production is from natural gas, 30% refinery products, 18% from coal, and the remaining 4% from water electrolysis. It can be seen from the figure that 96% of hydrogen is produced directly from fossil fuels and about 4% is produced indirectly by using electricity generated through fossil fuels.

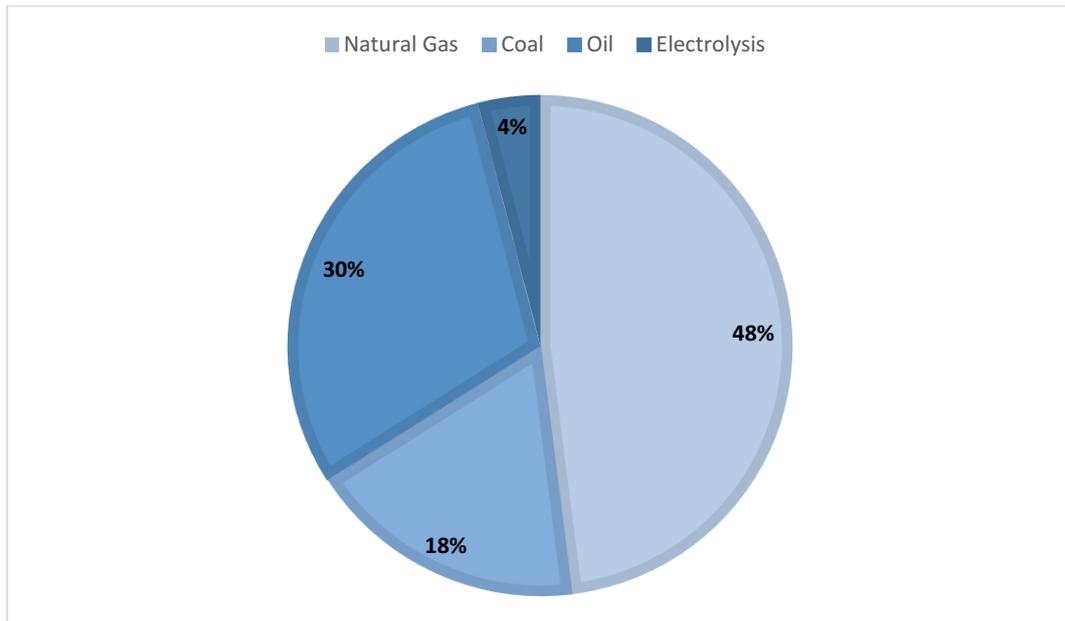


Figure 4 - The feedstock used in the current global production of hydrogen

The dependence on natural gas and coal means that hydrogen production today generates significant CO₂ emissions: 10 tonnes of carbon dioxide per tonne of hydrogen (tCO₂/tH₂) from natural gas, 12 tCO₂/tH₂ from oil products, and 19 tCO₂/tH₂ from coal.

For this reason, the goal of the next few years will be to produce “green” hydrogen from renewable energies instead of “grey” hydrogen from fossil fuels to reduce CO₂ emissions.

In the following sections the different technologies of production will be described in detail.

2.3.1 STEAM REFORMING PROCESS

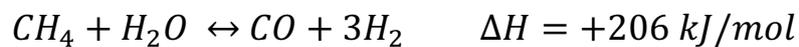
The steam reforming process, known as Steam Methane Reforming (SMR), is a well-developed and highly commercialized process through which approximately 48% of the world's hydrogen is produced. This method can also be applied to other light hydrocarbons such as butane, propane, gasoline and methanol but heavy hydrocarbons cannot be treated because they may contain impurities that would damage the catalysts.

The steam methane reforming process for pure hydrogen production consists of following stages:

- Desulphurization unit,
- Steam methane reformer,
- Shift reactor,
- Pressure swing adsorption,
- Methanation.

The first stage in the process is to purify the natural gas by a hydro-desulphurisation step in which the organo-sulphur compounds are reacted over a catalyst with recycled hydrogen to form hydrogen sulphide followed by absorption of that hydrogen sulphide in a zinc oxide bed through its conversion to zinc sulphide.

The second stage, a steam methane reformer, is based on the decomposition of methane and H₂O into hydrogen and carbon monoxide. The following chemical reaction is endothermic, so it requires a large amount of heat:



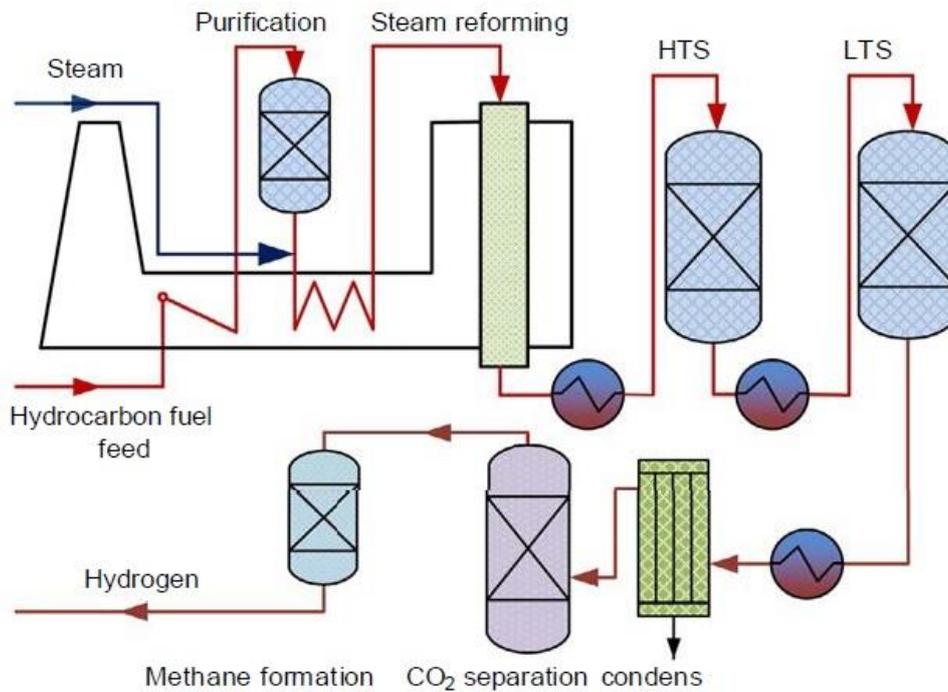
In the third stage, carbon monoxide and water are transformed into carbon dioxide and hydrogen, this phase is called "shift reaction" and occurs according to the following reaction:



This is an exothermic reaction.

Then there is the pressure swing adsorption unit, where the CO₂ is removed by adsorption with alkaline solutions.

In methanation, residual impurities consisting of CO, CO₂ and inert gases are removed, transforming them into methane.



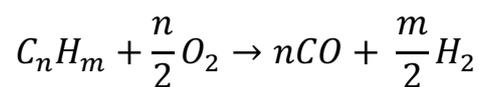
HTS: high temperature shift, LTS: low temperature shift

Figure 5 - Steam reforming process

2.3.2 PARTIAL OXIDATION OF HYDROCARBONS

Another method for hydrogen production is Partial oxidation (PO_x), that is a non-catalytic technology in which natural gas or a heavy hydrocarbon fuel is mixed with a limited amount of oxygen in an exothermic process.

The reaction for a generic hydrocarbon is the following:



The efficiency of the process is lower, about 50%, than that obtained by SMR technology, about 65%-75% and pure oxygen is required. The oxygen needed for the reaction is that contained in the atmosphere so mixed with a large amount of nitrogen.

Thus, with partial oxidation, an impure hydrogen flow is obtained which is heavily contaminated by nitrogen. If methane is used, the efficiency of this process reaches only 70% of that of steam reforming.

In reality *autothermal reforming* is often used, that is a process that combines the best aspects of steam reformer and partial oxidation.

Hydrocarbon and steam are mixed with oxygen at the head of the reactor where the exothermic reaction of partial oxidation takes place, which provides heat for the endothermic reaction of steam reforming. In the part of the reactor where the partial oxidation reaction occurs, the temperature is about 1200 °C.

2.3.3 GASIFICATION OF COAL

The gasification process consists in the partial, non-catalytic oxidation of a solid, liquid or gaseous substance which has the final objective of producing a gaseous fuel, consisting mainly of hydrogen, carbon monoxide and light hydrocarbons such as methane.

The production of hydrogen by gasification is a technology that finds many commercial applications thanks to the fact that coal resources are abundant and readily available in all parts of the world, but it is competitive with SMR technology only where the cost of natural gas is very high.

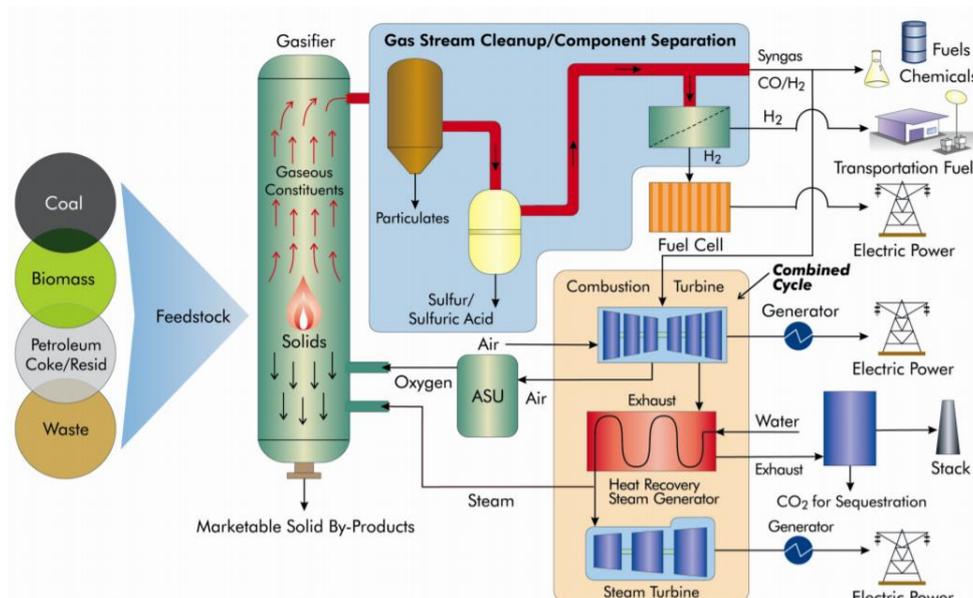


Figure 6 - Layout of gasification plant

The process can be simplified in the following steps:

1. Production of oxygen in an air separation unit (ASU);
2. Syngas production by partial oxidation of coal;
3. Desulfurization and cleaning of the product;
4. Shift conversion;
5. Purification of hydrogen.

For gasification there are three main methods: fixed-bed, fluidized-bed and entrained flow. All these methods employ steam, oxygen or air, to partially oxidize the coal and obtain the gas.

Fixed bed gasifiers produce a gas at low temperatures 425-650 °C, containing "devolatilized" products such as methane, ethane and a flow of liquid hydrocarbons containing naphtha, tar, oils and phenols.

In fluidized beds, some carbon particles are suspended in the gas stream while others go back to the denser part of the bed, and undergo gasification, at a temperature of about 1000 °C. Due to the low operating temperatures, highly reactive coals are mainly used, such as lignite and Brown-coal.

Entrained flow gasifiers are the most commonly used; in this process pulverized coal particles and gas flow move in the same direction and at high velocity, at a temperature of about 1250 °C. Thanks to high temperature products composed of H₂, CO and CO₂ are obtained. Due to the low residence time inside the reactor, the charge must be finely pulverized to ensure an adequate carbon conversion ratio.

Gasifiers produce polluting substances, mainly ash, sulphur oxides and nitrogen oxides, which must be removed before they become part of the gas produced. Their level depends both on the gasifier used and on the composition of the fuel.

The cleaning of entrained flow gasifiers involves a series of operations according to the different nature of the residues with a loss of efficiency, reliability and a significant increase in the costs of these systems. For this technology, the cost of the material used reaches almost 25% of the price of hydrogen produced. Compared to other technologies, excluding electrolysis, costs are slightly higher and it is not yet possible to achieve particular economies of scale.

2.3.4 GASIFICATION AND PYROLYSIS OF BIOMASS

The term *biomass* means all organic products deriving directly or indirectly from a photosynthesis process. A wide variety of biomass resources are used for the energy conversion. These can be grouped into four categories:

- Energy plants: herbaceous energy plants, woody energy plants, industrial plants, and agricultural and water plants.
- Agricultural residues and wastes: plant and animal wastes.
- Forest wastes and residues: wood processing and cutting residues and tree and bush residues.
- Industrial and urban wastes: urban solid wastes, sewage sludge, and industrial wastes.

Hydrogen and electricity can be obtained by exploiting the products derived from the treatment of biomass originating from municipal, industrial waste and discarded substances of agricultural and livestock production.

The available thermochemical technological systems are mainly two:

- Gasification consisting of a partial oxidation of a liquid or solid material at temperatures between 800 and 1100 °C.

The products are:

- Gas consisting of CO, H₂, CO₂, CH₄;
 - Tar means a fraction of heavy hydrocarbons condensable at room temperature;
 - Solid residue, *char*, consisting of the inert fraction of the treated material.
- Pyrolysis means the thermal degradation of organic matter in the absence or lack of oxygen. The pyrolytic process is an endothermic process, occurs at temperatures of 450-550 °C, in which biomass is decomposed to form a "bio-oil" consisting of 85% organic oxygenate substances and 15% water. The bio-oil is then subjected to the steam reforming process for the production of hydrogen.

An important environmental advantage of the use of biomass as a source of hydrogen is represented by the fact that the carbon dioxide emitted in the energy conversion does not contribute to increasing the total amount of CO₂ in the atmosphere.

Carbon dioxide is consumed by biomass during growth and only the same amount is returned to the environment during the conversion process.

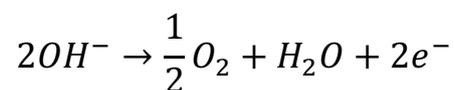
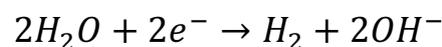
The limitation is that the hydrogen content in biomass is only 6-7% compared to 25% of natural gas.

2.3.5 ELECTROLYSIS OF WATER

The most well-known method of hydrogen production is the *Electrolysis process*; that is an electrochemical process that splits water into hydrogen and oxygen. Although this method is more expensive than steam reforming process, electrolysis can play an important role in the transition to a hydrogen economy because small structures can be built at existing service stations. In addition, electrolysis is well matched to intermittent renewable technologies.

The process is carried out inside an electrolyser, an electrochemical cell consisting of an anode and a cathode, separated by an electrolyte. A direct current is passed through the two electrodes in order to break the water molecules and then form H₂ at the cathode (negative electrode) and O₂ at the anode (positive electrode).

When the appropriate potential difference is applied to the electrodes, the two half-reactions of reduction (at the cathode) and oxidation (at the anode) begin on their surface:



These give rise to the overall reaction:



As a result of the reactions, hydrogen and oxygen are collected and stored in suitable pressurised containers.

The electrolytic cell consists of a container containing:

- An acidic or alkaline ionic solution;
- A diaphragm that allows the passage of ions but prevents oxygen and hydrogen from mixing;
- A pair of electrodes, generally made of platinum.

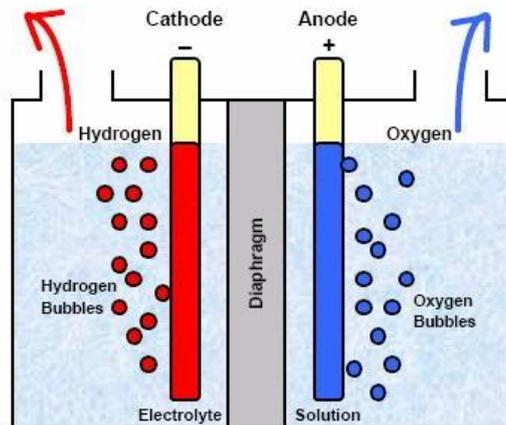


Figure 7 - Electrolytic cell

Despite the abundant availability of water, only a small part of the world's hydrogen production, about 3%, is achieved through this process. In fact, the realization of the electrolysis of water requires a very high expenditure of electricity, which therefore makes the process expensive, and limits its use only in applications that require a hydrogen flow with very high purity.

Electrolysis requires water as well as electricity. Around 9 litres of water are needed to produce 1 kg H₂, producing 8 kilograms of oxygen as a by-product, which at smaller scale can be used in the health care sector or at a larger scale for industrial purposes. If all of today's dedicated hydrogen production of around 70 Mt H₂ were to be produced by electrolysis, this would result in a water demand of 617 million m³, which would correspond to 1,30% of the water consumption of the global energy sector today or roughly twice the current water consumption for hydrogen from SMR (345 million m³ of water for 52 Mt H₂ from SMR).

To solve this problem a possible solution, still in the experimental phase, could be steam electrolysis, which consists in the dissociation of water with steam at high temperatures, around 900 - 1000 °C.

This would allow to accelerate the reactions and reduce the losses of energy due to the polarization of the electrodes, increasing the efficiency of the system.

Another possibility is to feed the water dissociation process through electricity produced from *renewable sources*. In recent years, however, with declining costs for renewable electricity, in particular from solar PV and wind, interest is growing in electrolytic hydrogen. The efficiency of electrolyser systems today ranges between 60% and 81% depending on the technology type and load factor.

The main electrolyser used are:

1. *Alkaline electrolyzers* consist of two electrodes, separated by a semi-porous membrane, and an aqueous alkaline electrolyte. This electrolyte is usually a solution consisting of 30% by weight of sodium hydroxide or potassium hydroxide. They typically achieve efficiencies of 60-70%.

Alkaline electrolysis is characterised by relatively low capital costs compared to other electrolyser technologies due to the avoidance of precious materials.

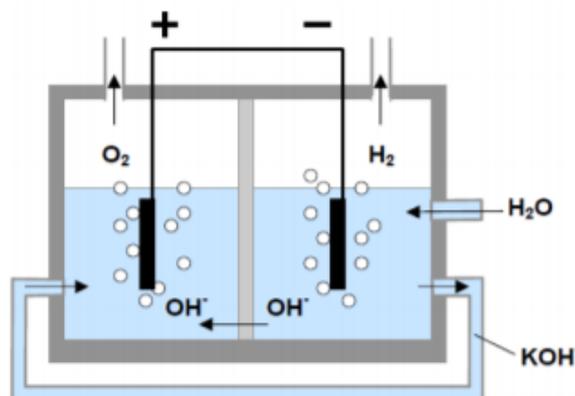


Figure 8 - Layout of alkaline electrolyser

2. *Proton exchange membrane (PEM) electrolyser* are characterized by efficiency levels generally higher than alkaline ones. Their peculiarity is to have as electrolyte a particular material, called NAFION, which is an excellent conductor of protons. The catalysts used as electrodes are platinum or iridium based. Their overall costs are currently higher than those of alkaline electrolyzers, and they are less widely deployed.

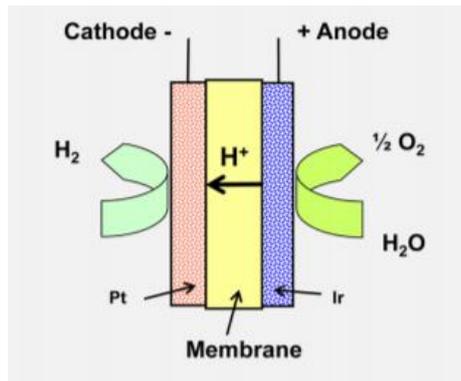


Figure 9 - Layout of PEM electrolyser

3. *Solid oxide electrolysis cells (SOECs)* use ceramics as the electrolyte and have low material costs.

They operate at high temperatures 650-850 °C and with a high degree of electrical efficiency.

Because they use steam for electrolysis, they need a heat source. Nuclear power plants, solar thermal or geothermal heat systems could also be heat sources for high-temperature electrolysis.

Unlike alkaline and PEM electrolyzers, it is possible to operate an SOEC electrolyser in reverse mode as a fuel cell, converting hydrogen back into electricity, which means it could provide balancing services to the grid in combination with hydrogen storage facilities.

It is also possible to use a SOEC electrolyser for co-electrolysis of steam and carbon dioxide, producing a gas mixture (carbon monoxide and hydrogen) for subsequent conversion to a synthetic fuel.

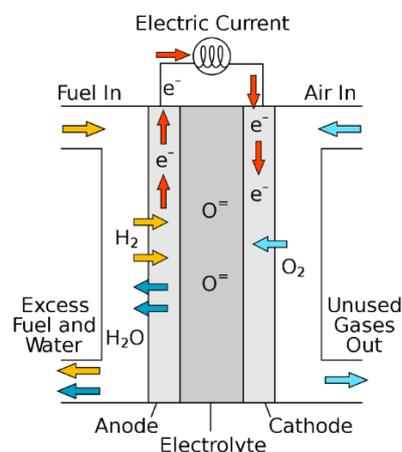


Figure 10 - Layout of SOEC electrolyser

In the Table 2 are summarised the main technical and economic characteristics of different electrolyzers.

Table 2 - Comparison between three different of electrolyzers

	Alkaline electrolyzers			PEM electrolyzers			SOEC electrolyzers		
	Today	2030	Long Term	Today	2030	Long Term	Today	2030	Long Term
Electrical efficiency (% LHV)	63-70	65-71	70-80	56-60	63-68	67-74	74-81	77-84	77-90
Operating pressure (bar)	1-30			30-80			1		
Operating temperature (°C)	60-80			50-80			650-1000		
Stack lifetime (operating hours)	60000 - 90000	90000 - 100000	10000 - 150000	30000 - 90000	60000 - 90000	100000 - 150000	10000 - 30000	40000 - 60000	75000 - 10000
Load range (% relative to nominal load)	10 - 110			0 - 160			20 - 100		
Plant footprint (m²/kW_e)	0,095			0,048					

In the last decade there has been an increase in the installations of electrolyzers, in particular of PEM technology. Most of the projects are in Europe but project have been also started or announced in Australia, China and Americas.

The average unit size of these electrolyser has increased in recent years from 0,10 MW_e in 2000–2009 to 1,00 MW_e in 2015–2019.

In the Figure 11 is showed the development of electrolyser capacity additions for energy purposes and their average unit size.

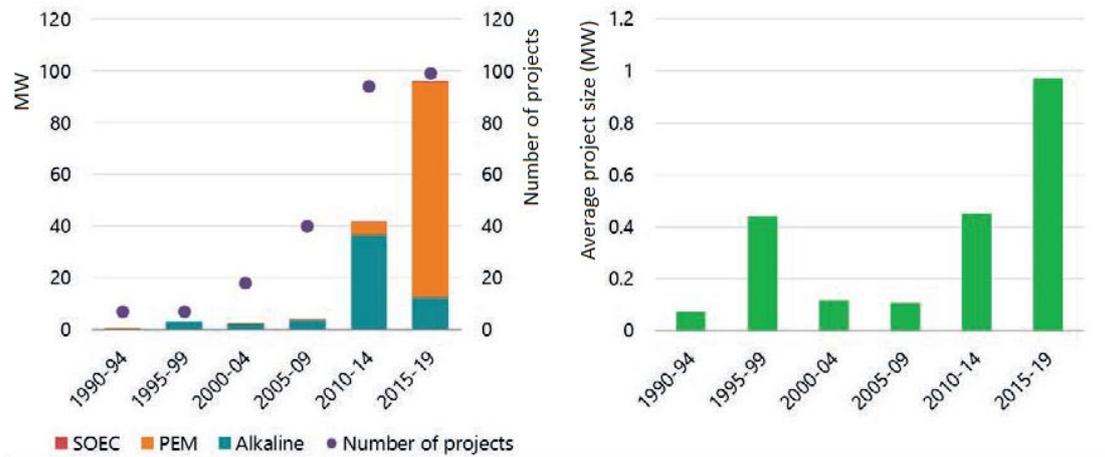


Figure 11 - Development of electrolyser capacity additions for energy purposes and their average

2.3.5.1 THE PURITY OF WATER

Since the only products of the electrolytic reaction are hydrogen and oxygen and the consumption of electrolyte is, unless physical losses, theoretically zero, any other substance injected into the cell with the supply water tends to accumulate there. It is important that the water is as pure as possible, with particular regard to:

- Chlorides: The Cl ion has a corrosive effect on the nickel deposit of anodes and therefore tends to accelerate their consumption under anodic discharge, although this influence is greatly mitigated by the high alkali concentration. Long-term experience shows that a nickel layer of 50 μm decreases by 0,3 μm in 10000 working hours and consumption remains virtually unchanged as the chloride content (Cl) varies. It can be concluded that this anion does not have excessively harmful effects. The indicated wear speed is so small that the life of the galvanic deposit can appear virtually unlimited. However, the decrease in thickness could be greatly accelerated by the presence or onset of porosity in the deposit, such as to expose the iron substrate to the anode discharge. Any contact with diaphragms should also be considered as an adverse circumstance to the integrity of the deposit. Finally, any stoppage and subsequent resumption of electrolysis imply a small but not negligible loss of nickel,

especially if, for reasons of personnel safety, during the shutdown the electrolysis battery is short-circuited, through a small resistance, in order to quickly discharge the residual voltage (about 1 V per cell).

- Carbon dioxide: Each trace of carbon dioxide in the water reacts with hydroxide to form the corresponding alkaline carbonate. Although the carbonate content which thus accumulates in the electrolyte can never in practice reach a level capable of exerting corrosive effects on the nickel deposit, it can, beyond a certain limit, significantly reduce the conductivity of the solution. In practice this does not occur up to a level of at least 2-3% Na₂CO₃ or K₂CO₃.
- Organic substances: It is essential that the supply water is free from saponified substances; even if present only in small traces, they form annoying foams, which tend to overflow outside the cells and within the gas supply lines, causing electrolyte losses. The water itself to be demineralized must be free from such poisons in analysable quantities, as well as the materials with which the electrolyte circuit can come into contact (gaskets, plastic pipes, natural or synthetic coatings) must be free of them.
- The conductivity of the feed water provides the most immediate indication of its saline content. Therefore, purification plants are always equipped with a conductometer, which automatically triggers a signal, as soon as the conductivity has exceeded a certain allowable limit, so as to make necessary the regeneration of resins. The default value for this limit is $5 \cdot 10^{-6} \Omega^{-1} \text{cm}^{-1}$.

2.3.5.2 THE PURITY OF HYDROGEN

The purity of a gas is a parameter that identifies the amount of impurities (other gases or substances) that the gas itself contains. The higher the purity, the higher the quality of the gas, since it contains other substances in very limited amounts.

It is usually expressed as a grade prefixed with letter N, giving the “number of nines” in the percentage of decimal fraction. For gasses, the number of nines is generally written after letter N rather than before.

The Table 3 describes purity grade and percent purity.

Table 3 - Purity of hydrogen

Percent Purity	Purity Grade (nines scale)
90 %	N1
99 %	N2
99,9 %	N3
99,97 %	N3.5
99,995 %	N4.5
99,999 %	N5
99,9999 %	N6

The price for the purchase of a standard tank (with an equivalent volume of 50 litres of water) containing 10 Nm³ of H₂ could vary, in fact, between 3-5 €/ Nm³, for a purity grade 4,5, and 15-20 €/ Nm³, for a purity grade 5 or higher.

2.3.5.3 EXAMPLE OF PILOT FACILITY FROM RENEWABLE SOURCE

Snam, Italian energy infrastructure company, has developed a reference case situated in Sicily, which combines renewable hydrogen production from wind power in an electrolyser, its transport in existing pipelines, its use in a local refinery as well as for a hydrogen train and as part of the local gas grid for household heating.

Sicily has been chosen because is a great location for hydrogen production with the availability of cost competitive solar renewables given high solar radiation in the region, and the potential to import from North Africa at even lower cost.

The test was performed in an extensive network of gas pipelines that already exist. The area has a transmission network of 1100 km national pipelines and 1500 km regional pipelines, as well as an extensive distribution network covering all major cities.

The project will be concluded in 2022 and it could require building 50 MW electrolyser connected to wind or solar parks, then transporting hydrogen through pipelines to one refinery and blending it into local districts for heating.

The total cost for the initial phase estimated to be in the range of 70-90 Eur million for first 10 years of operations, including the cost of renewable electricity feeding, partially offset by avoided cost of grey hydrogen production of 30-40 Eur million over the same period.

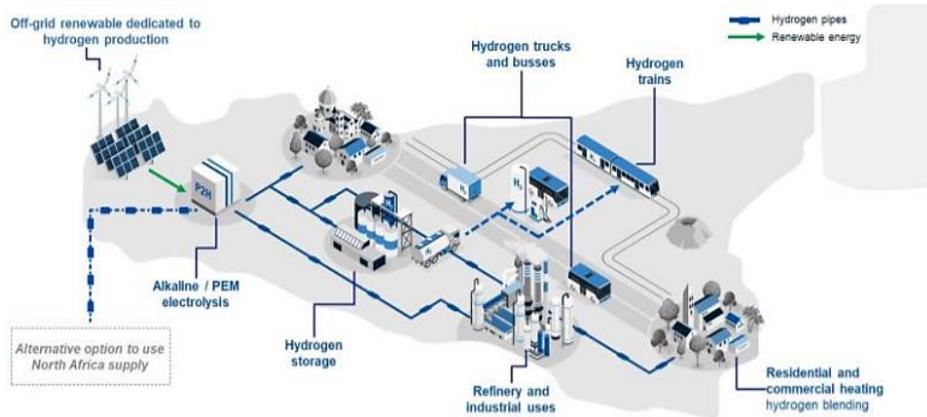


Figure 12 - Pilot facility in Sicily

Another example is the INGRID project that has performed an experimental plant in Troia, in Puglia region, as it is an area that records a very large number of wind and photovoltaic systems. The pilot plant is 39 MWh, consisting of a 1,20 MW electrolyser, a solid hydrogen storage system, a fuel cell and ICT real-time monitoring and control systems.

Using solar and wind energy, the hydrogen produced by the electrolyser in gaseous form is absorbed by magnesium discs, which form stable compounds with hydrogen called magnesium hydrides and allow it to be stored in solid form.

In this way, hydrogen can be transported safely and made available to industrial users, or it can be extracted from magnesium discs and used as zero emission fuel for electric mobility. In addition, thanks to the fuel cell, the accumulated hydrogen can be re-converted into electricity and re-injected into the network when the loading conditions allow it.



Figure 13 - Pilot facility in Puglia

2.3.6 COST OF PRODUCTION

To qualitatively assess the costs derived from each hydrogen production technologies both from fossil fuel and renewable, variables such as energy source, feed stock and hydrogen production cost (per kg of hydrogen) have been shown in the Table 4.

The cost of hydrogen is strongly affected by the production technology's advancement level, availability of existing infrastructure, and the feedstock price. According to the table, the most financially advantageous methods for hydrogen production are steam methane reforming, coal, and biomass gasification. Wind and solar electrolysis give the highest production cost per kg of hydrogen. Since one of the major advantages of electrolysis is its local applications, distributed, small-scale production assumption is made when calculating the cost of electrolysis.

Table 4 - Comparison of different hydrogen production methods

Production technologies	Energy source	Feedstock	Capital cost (M€)	Hydrogen price (€/kg)
SMR	Standard fossil fuels	Natural gas	160 - 202	1,90 – 2,00
Gasification of coal	Standard fossil fuels	Coal	388 - 485	1,20 – 45,00
Gasification of biomass	Internally generated steam	Woody biomass	5,70 – 47,50	1,60 – 1,80
Pyrolysis of biomass	Internally generated steam	Woody biomass	3 - 47	1,10 – 2,00
Solar thermal Electrolysis	Solar	Water	20 - 374	4,50 – 9,40
Electrolysis (PV based)	Solar	Water	10 – 48,5	5,15 – 21,00
Electrolysis (Wind based)	Wind	Water	444 - 450	5,20 – 5,40

2.4 STORAGE OF HYDROGEN

Transport and storage costs will play a significant role in the competitiveness of hydrogen.

Hydrogen can be used to store energy in large quantities for long periods and to move it over very long distances. If hydrogen can be used close to where it is made, these costs could be close to zero. However, if the hydrogen has to travel a long way before it can be used, the costs of transmission and distribution could be up to three times as large as the cost of hydrogen production.

Today hydrogen is usually stored and delivered in compressed gas or liquid form. The majority is either produced and consumed on-site (around 85%) or transported via trucks or pipelines (around 15%). The competitiveness of the different options will depend on the distance over which hydrogen is transported, and on scale and end use.

In the Figure 14 is shown a schematization of the various modes of collection, transmission, distribution and demand of hydrogen.

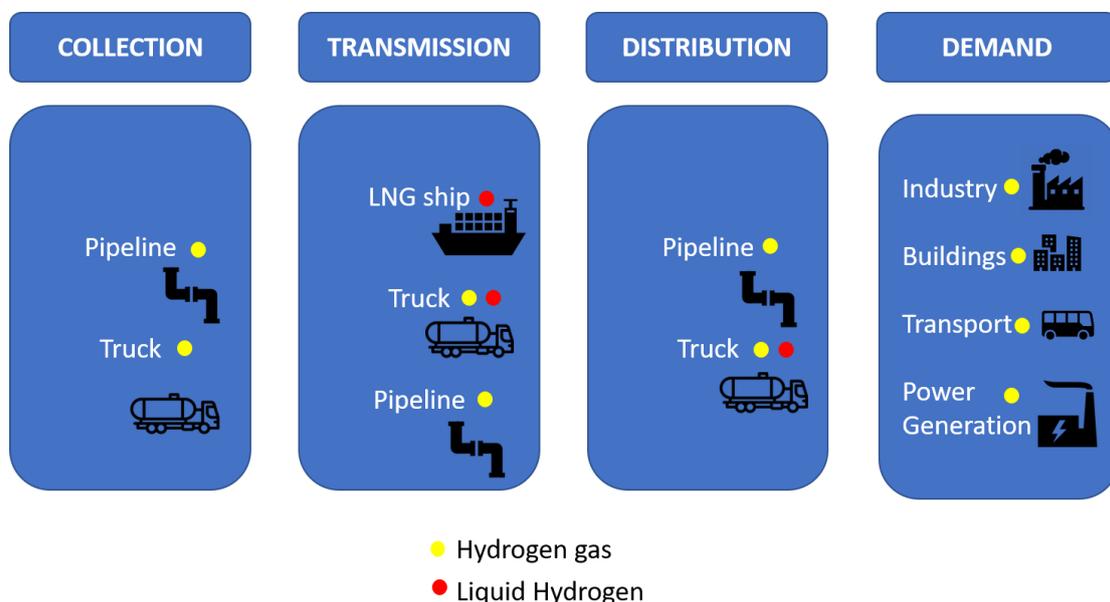


Figure 14 - Chain of collection, transmission, distribution of hydrogen

The major obstacle to the widespread use of hydrogen is the storage. Hydrogen in the form of gas takes up 3000 times more space than a gas with the same amount of energy at room temperature and pressure. For this reason, three hydrogen storage methods can be considered as practicable as compressed gas, in the liquid state and by chemical accumulation.

2.4.1 STORAGE AS COMPRESSED GAS

The easiest way to store hydrogen is to use it in compressed form in a high-pressure resistant tank at room temperature.

A high-pressure hydrogen storage system is basically composed of a cylindrical tank, a pressure regulator to reduce the pressure before feeding it into the propulsion system and valves for the control of the gas flow. The tank material is one of the key problems of these systems. In fact, hydrogen is capable of spreading in materials that are impermeable to other gases and, reacting with carbon which is a component of steel, can cause a decrease in the solidity of the tank walls. To solve this problem, chromium-enriched steels and alloys have been used. For larger tanks, reinforced plastic composite materials were used. The highest pressure used is 350 bar, but some tanks can operate 700 bar.

Tanks should have explosion resistance at least twice the fuel pressure. For this reason, it is expected that in the future cylinders will be used consisting of three layers: an internal polymer, an intermediate carbon fibre able to withstand high traction, a more external one able to protect the system from mechanical and corrosive damage.

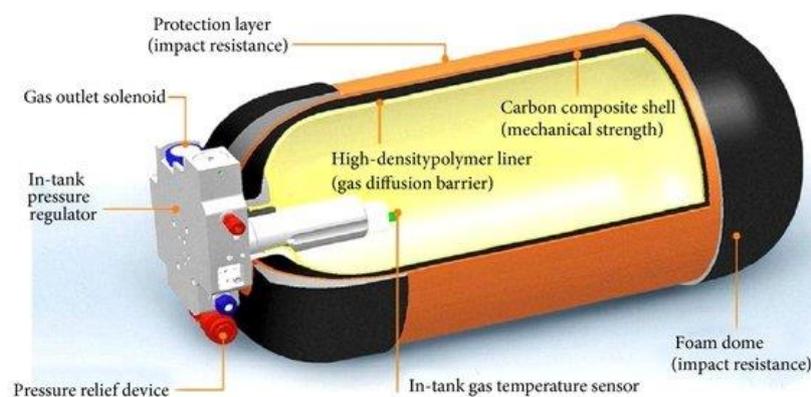


Figure 15 - Compressed hydrogen gas storage tank

2.4.2 STORAGE AD LIQUEFIED HYDROGEN

The hydrogen is stored at -253°C in atmospheric pressure in fairly well insulated tanks. Because the hydrogen is in the liquid form, it contains 3 times more energy than the equivalent weight petrol and 2,7 times more volume is required in case of containing the equivalent energy.

This type of configuration is very interesting for long distance transport and for containing fuel for spacecraft and airplanes. Liquid hydrogen tanks are generally cylindrical and constructed of thin-walled metal alloys. To keep the content as isolated as possible from the external heat, these tanks are wrapped in a multilayer thermal insulation composed of metal sheets and glass wool. At the same weight, a liquid hydrogen tank has a much greater capacity than that of compressed gas.

The problems related to this technology are:

- The cooling process requires an expenditure of energy normally equal to 30 - 40% of the fuel contained;
- The tanks are very expensive;
- The boiling of part of the liquid hydrogen needs to be vented outside, requiring safety measures and generating capacity losses, even when the engine is off;
- Supply infrastructure requires large investments and significant security measures.

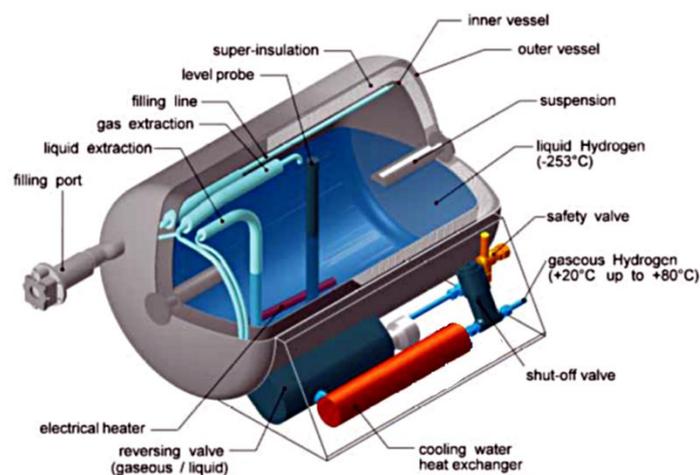


Figure 16 - Liquefied hydrogen tank

In the Table 5 are shown the cost comparison of compressed and liquid hydrogen storage method.

Table 5 - Cost of compressed and liquid hydrogen storage methods

Storage method	Raw cost of H ₂ (€/kg)	Cost to process H ₂ (€/kg)	Cost to transport H ₂ (€/kg)	Cost of on-site storage of H ₂ (€/kg)	Refuelling station cost H ₂ (€/kg)	Delivered cost of H ₂ (€/kg)
Compressed Hydrogen	1,07	0,62	0,62 (pressurized tank)	0,40 (high-pressure storage tank)	0,67	3,40
Liquid Hydrogen	1,01	0,99	0,19 (cryogenic tank)	0,20 (cryogenic storage including boil off losses)	0,60	3,05

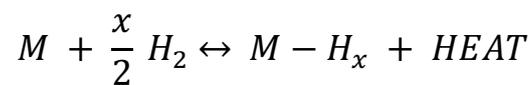
2.4.3 METAL HYDRIDE

One of the technologies best suited to hydrogen storage, especially for mobile applications, is solid state storage, through which hydrides are formed.

Metals, intermetallic compounds and alloys are used for this purpose.

Hydrides are a solid compound capable of trapping hydrogen at relatively low pressures; where the gas penetrates within the metal's crystalline lattice, and releasing it at high temperatures.

The reaction for a generic metal is:



In the forward reaction, heat is required for the absorption of hydrogen to form a *metal hydride*. When this happens, hydrogen is distributed compactly throughout the metal hydride lattice. The reaction is reversible and its direction is determined by the pressure of the hydrogen gas.

If the pressure is above the equilibrium pressure of the hydrogen gas, the reaction proceeds to the right to form a metal hydride (Stage 2 in the Figure 17); if the pressure drops below the equilibrium, hydrogen is liberated and the alloy returns back to its original state.

This equilibrium pressure is dependent on temperature; it increases with increasing temperature and vice versa. Metal hydrides is thus able to adsorb and release hydrogen reversibility without significant deterioration.

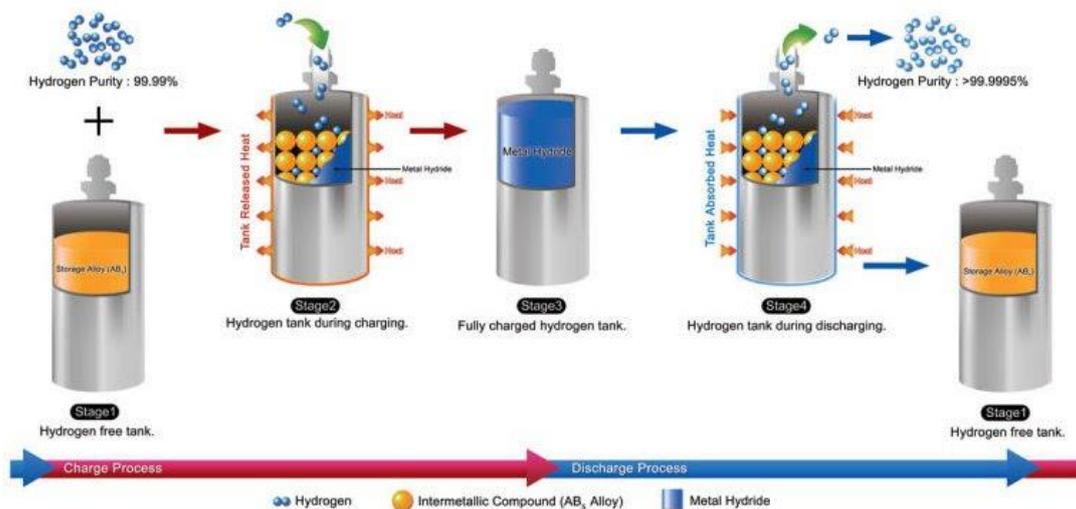


Figure 17 - Hydrogen charging and discharging process using metal hydride storage

To do this, it is necessary to work with a certain pressure, about 25-100 bar, keeping the pressure constant for 90% of the process and then increasing it in the final session. The loading of a hydride is an exothermic absorption operation with heat generation and it will therefore be necessary the presence of a cooling system to keep under control the average temperature during the process. The final purpose of this process is the use of the same hydrogen contained in the metal lattice, namely dehydrogenation. This process is endothermic; initially the pressure is kept high and tends to lower it as the hydride is depleted of hydrogen. The endothermal feature is interesting for the possibility of coupling this type of storage with a fuel cell that provides heat in the case of a vehicular application.

The hydrides are divided into high or low temperature hydrides, depending on the absorption/desorption temperature. In high-temperature ones, desorption occurs between 150 and 300 °C, while in low-temperature ones between 20 and 90 °C. The storage capacity is higher for high-temperature hydrides.

This technology allows to reach energy densities potentially greater than compressed hydrogen and comparable to those of liquid hydrogen.

Depending on the structure of the absorbent grid and the characteristic of the accumulation alloy, the release pressures and the accumulation temperature can be varied, making the system reversible. The higher the absorption surface, the greater the amount of hydrogen accumulated, which tends to pulverize the hydride.

A hydride tank is three times larger and four times heavier than a petrol tank that produces the same energy. Assuming that a metal hydride tank weighs 70 kg it will have the capacity to contain 4 kg of hydrogen and will be able to travel approximately 400 km (considering an average saloon car). Further advantages are the ability to maintain gas at normal temperature and pressure. Safety is also a point in favour of the risk of unwanted losses, even in the event of an accident, is minimal, because the release of hydrogen is not a spontaneous process.

2.4.4 NANOSTRUCTURES OF CARBON

A new hydrogen storage technology involves the use of *carbon nanostructures* (nanotubes and carbon nanofibers); that are microscopic structures of carbon fibres that allow a certain amount of hydrogen to be stored in them by exploiting the affinity between carbon and hydrogen atoms. The storage process in these materials is similar to that for metal hydrides. The gaseous molecules of hydrogen are absorbed into the microscopic pores present on the surface of the carbon grains, then remains trapped in the cavities of the material and is released only when the temperature is increased. The development of such storage technologies is still at an experimental stage but they seem to be optimal candidates for storage in vehicular applications; it is estimated that in a 6,50 kg tank it is possible to contain up to 4 kg of hydrogen.

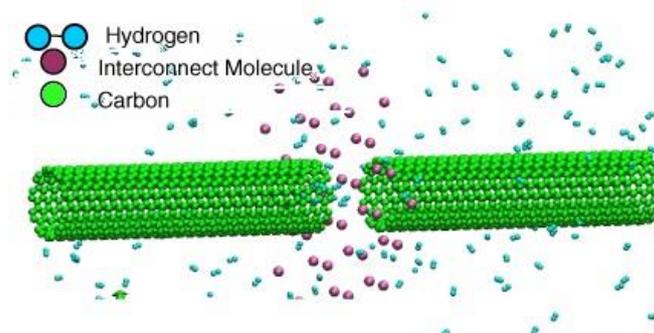


Figure 18 – Nanotube of carbon

2.5 TRANSPORT OF HYDROGEN

The low energy density of hydrogen means that it can be very expensive to transport over long distances. Nonetheless, a number of possible options are available to overcome this hurdle, the type of hydrogen distribution is based on the storage techniques described before.

2.5.1 TRANSPORT OF COMPRESSED HYDROGEN

Compressed hydrogen is mainly transported by trucks and pipelines.

The trucks are made up of high-pressure cylinders, the best are the trucks composed of several steel cylinders mounted on a protective framework and can contain from 63 to 460 kg of hydrogen compressed at a pressure of only 20 MPa.



Figure 19 - Truck for compressed hydrogen

Compressed hydrogen can also be transported in pipelines such as those used for natural gas. Compared to natural gas, hydrogen has lower molecular weight and viscosity and consequently pipes of equal diameter operating at the same working pressure allow the flow of a greater volumetric flow rate with equal loss of load along the line. Hydrogen requires three times more pumping pressure than methane, due to the lower density. In addition, if the ideal diameter of the pipelines is 1,4 meters, that of the hydrogen pipelines is 2 meters.

On the other hand, the lower calorific value of hydrogen per unit of volume, about one third of the value of natural gas, implies that the energy transported is, under the same conditions, lower than that relating to natural gas.

In particular, this effect is particularly evident at low pressures while it is almost irrelevant for line pressures of the order of 100 bar. It follows that to optimise the transport of hydrogen it is necessary to operate at pressures of not less than 50-60 bar.

In addition, intermediate recompression stations, such as for natural gas which are positioned at 150 m, must be used for the transport of gas over long distances to recover pressure losses along the line which are of the order of about 15 bar.

For natural gas the energy consumption of each recompression station is of the order of 0,15% ÷ 1,50% of the fuel power. In the case of hydrogen transport, due to the increased compression work due to gas characteristics, the relative consumption of recompression stations is of the order of 0,50% ÷ 4,60%. Taking as an example lines of transport from 48" operating at about 70 bar, the consumption of hydrogen by recompression would be of the order of 4,70% per 1000 km, compared to 1,30% of natural gas, thus making such installations inexpensive for great distances.

On the contrary, the transport and distribution of hydrogen for relatively small distances, such as interregional infrastructure, has low consumption and seems applicable in particular for the connection of production plants to distribution network or to natural gas transmission lines.

The problem to take into account for the construction of steel pipes for the transport of hydrogen is the phenomenon called **Hydrogen embrittlement**. The embrittlement leads to a decrease in the ductility of the metal and can lead to fractures of the material. The most important aspect is that the material may present fractures even if subjected to much lower stress than the yield stress. The embrittlement by hydrogen increases with the pressure of hydrogen and its purity and it also increases with the content of carbon and manganese that facilitate the formation of martensite more sensitive to damage by hydrogen.

Metal materials used in hydrogen transport pipelines shall have a maximum hardness of approximately 22 HRC (Rockwell hardness C) or 250 HB (Brinell hardness); this is approximately equivalent to a limit tensile strength of approximately 800 MPa.

These limits must be respected by the welds present, which are usually more susceptible to embrittlement than the base material. In order to maintain these strength and hardness values, lower strength steels should be used so the limit becomes about 500 MPa.

We can summarize that for the choice of material is good:

- use materials with yield strength not exceeding 290 MPa (corresponding to API grade 5L X42) or 360 MPa (API grade 5L X52);
- use low carbon steels (about 0,20% by weight) and manganese steels ($\leq 1-1,20\%$ by weight).

Hydrogen pipelines of significant size are currently present in several countries. There is a network of about 170 kilometres in Northern France, for a total of over 1500 kilometres in the whole of Europe. North America also has over 700 kilometres of hydrogen pipeline. Distribution networks for liquid hydrogen, on the other hand, which are particularly expensive and difficult to manage, have been built only for particularly specialized applications, such as the refuelling of spacecraft.

One of the first examples of a hydrogen pipeline was built in 1938 by Chemische Werke Huis AG, now owned by Air Liquide, in Germany, in the Ruhr industrial zone. The total length of the line is 240 km and many production sites and industrial users are interconnected. The line, made of SAE1016 steel, low in manganese and with mechanical properties similar to API 5L X46 steel, is characterized by diameters between 6" and 10" and an operating pressure of about 25 bar.

Nowadays, most hydrogen pipelines are made using carbon steels, with a low manganese content similar to API 5L Gr steels. B and API 5L X46.

Only in the United States some lines, a few kilometres long and 5 cm in diameter, were made of austenitic 316 SS stainless steel.

Available data from some of the world's most important hydrogen transport lines are presented in the Table 6; empty cells are due to lack of data.

Table 6 - Characteristics of pipes in the world

Name Localization	Material	Diameter	Length (km)	Pressure (kPa)	Purity of gas	Active
EUROPE						
Air Liquid- Chemische Werke Huis AG, Germany	SAE1016 without welding	6''-10''	215	Until 2500	Raw gas	X
Air Liquide, France, Netherlands, Belgium	Carbon Steel, without welding	Until 12''	879	6500- 10000	Raw and pure	X
Air products, Netherlands			45			X
ICI Billingham, UK	Carbon steel		15	30000	Pure	X
Linde, Germany			50			
NORTH AMERICA						
Air Products, Houston, USA		4''-12''	100	345- 5500	Pure	X
Air Products, Louisiana	ASTM 106	3'' ½ – 11''	48.3	3450		X
Air Products, Sarnia			3			X
Air Products, Texas	Carbon steel	4''	8	5500	Pure	X
Air Products, Texas	Carbon steel	8'' sch 40	19	1400	Pure	X
AGEC, Alberta, Canada	Gr.290 (5LX X42)	10'' sch 10	3.7	3800	99,90%	X
American Air	API 5LX42,	3'' to 14''	390	5100		X

Liquide Texas / Louisiana, USA	X52, X60					
Cominco B.C., Canada	Carbon steel, ASTM A53 without welding	5 mm	0.6	> 30000	62-100%	Standby
Hawkeye Chemical, Iowa	ASTN A53 Gr. B	5" ½	3.2	2750		X
Gulf Petroleum Cnd, (Petromont – Varnnes)	Carbon steel without welding	6" sch 40	16		93,50% H ₂ 7,50% methane	X
LASL, N.M.	ASME A357- Gr. 5	1"	6,4	13800		NO
Los Alamos, N.M.	5 Cr. – Mo (ASME A357 Gr. 5)	30 mm	6	13800	Pure	NO
NASA – KSC, Fla	AISI 316 SS	50 mm	1.6-2	42000		X
NSA – MSFC, Ala	ASTM A106-B	76,20 mm	0,091	34500		X
Philips Petroleum	ASTM A524	203,20 mm	20.9	12800		X
Praxair, 6 states	Carbon steel		450		Pure	X
Rockwell International S.	SS- 116, carbon with 1,5% C, 12% Cr, 0,7% Mn	250 mm		>100000	Ultra - pure	

The figure 20 and 21 show networks of gas pipelines in the world.

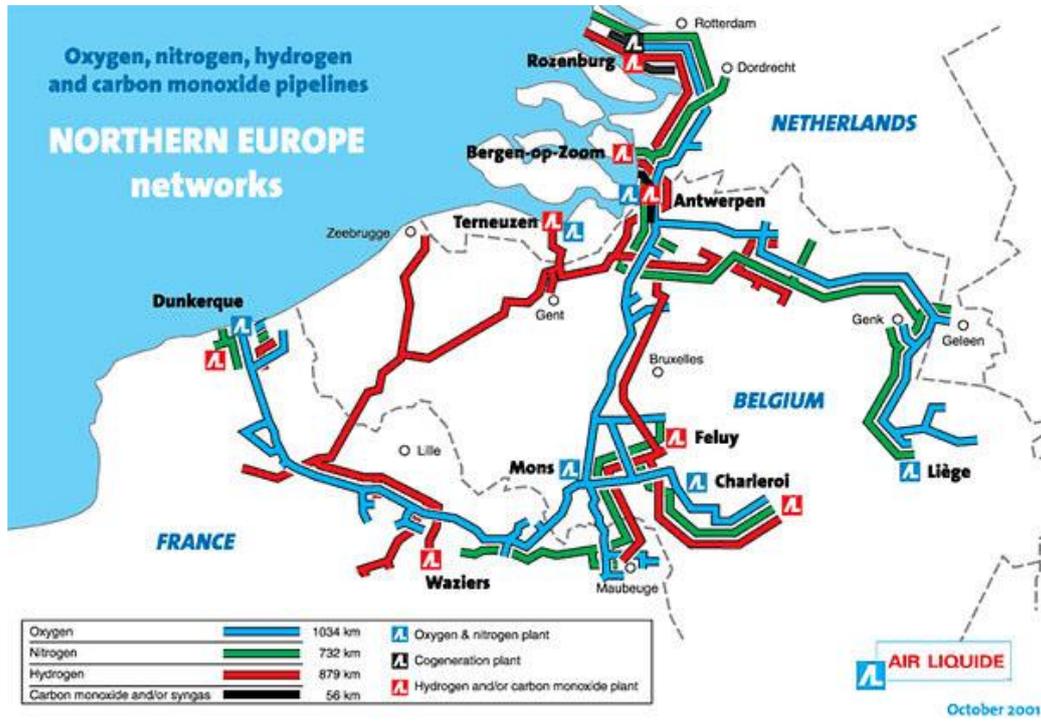


Figure 20 - Pipelines in North Europe



Figure 21 - Pipelines in the USA

2.5.2 BLENDING WITH NATURAL GAS

Blending hydrogen into natural gas pipeline networks is another way to delivering pure hydrogen to markets, using separation and purification technologies downstream to extract hydrogen from the natural gas blend close to the point of end use.

Blending hydrogen into the natural gas infrastructure that already exists allow to avoid the significant capital costs involved in developing new transmission and distribution infrastructure. Further, the environmental benefit is the net reduction in CO₂ emissions.

From the following graph in the Figure 22 we can see how CO₂ emissions decrease as the volumetric concentration of H₂ increases.

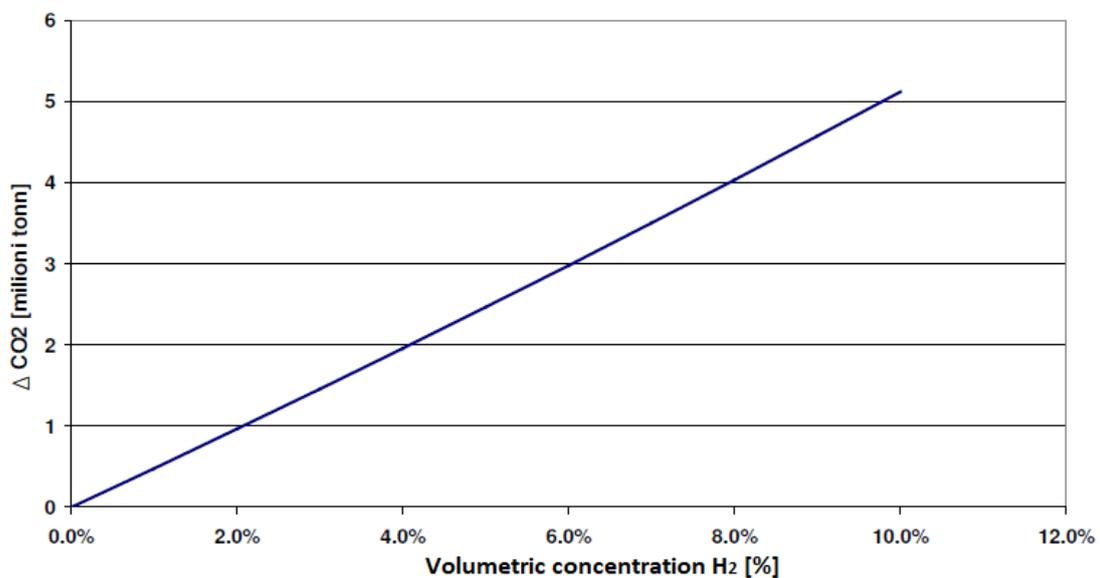


Figure 22 - CO₂ emissions vs Volumetric concentration H₂

Materials considered suitable for the transport of pure hydrogen are characterised by a yield strength not exceeding 360 MPa (API grade 5L X52) and preferably less than 290 MPa (API grade 5L X42). The most commonly used steels for the natural gas network are API 5L B X52 and X60 and constitute a risk factor to be considered especially in the case of mixtures with volumetric hydrogen concentrations of 20-25% or higher.

The most recent lines for the transport of natural gas are made with materials with a lower carbon content, which therefore have a chemical composition compatible with the presence of hydrogen.

As far as welding is concerned, the standards referred to include materials with a low diffusible hydrogen content and therefore already partially reflect the needs of hydrogen operation.

For flanged joints, ASTM A105 and MSS SP44 F52 and F50 steels that have an equivalent carbon level of less than 0,48-0,50% are considered to be at the limit of compatibility with hydrogen, being 0,43% the maximum recommended value for use with hydrogen.

A check shall also be carried out with regard to non-metallic materials in the network, such as elastomers, lubricating materials and sealing gaskets. For example, most elastomers are thought to be compatible with hydrogen, although attention should be paid to hydrogen permeation values through these materials which are on average higher than metals.

As a general rule, for volumetric hydrogen concentrations up to 10-15%, the current materials can be used; in particular the X52 also for concentrations up to 20-25% while for the X60 and X62, it is reasonable to believe that hydrogen concentrations of 10% should not be exceeded.

Many countries have looked at adding hydrogen into the existing natural gas networks. For example, in the USA, it would be possible to introduce amounts from 5 vol % to 15 vol % hydrogen without substantial negative impact on end users or the pipeline infrastructure but adding more hydrogen would require expensive conversions of appliances. In Germany the limit has been set up to 10 vol %. In principle, gas at concentrations of up to 10 vol % hydrogen can be transported in the existing natural gas network without the risk of damage to gas installations, distribution infrastructure.

In April 2019, Snam, an Italian energy infrastructure company, began testing the introduction of a 5% hydrogen by volume and natural gas mixture into the Italian gas transportation network. The experiment has been done in Contursi Terme, in the province of Salerno, and provides for the supply of H₂NG (mixture of hydrogen and gas) to two industrial companies in the area, a pasta factory and a mineral water bottling company.

The mixture of natural gas and hydrogen injected respected the fuel gas quality parameters reported in the Ministerial Decree of 18 May 2018 showed in the Table 7.

This decree does not explicitly mention a maximum percentage of hydrogen that can be contained in a mixture with fuel gas, but defines ranges of values for the gas quality parameters (PCS, Wobbe Index and relative density) that must be respected.

Table 7 - Gas quality parameters from Ministerial Decree 18 May 201

Parameter	Acceptability values	Unit of measure
Methane	(*)	
Ethane	(*)	
Propane	(*)	
Iso-butane	(*)	
Normal-butane	(*)	
Iso-pentane	(*)	
Normal-pentane	(*)	
Hexanes and higher	(*)	
Nitrogen	(*)	
Oxygen	≤ 0,60	% mol
Carbon dioxide	≤ 2,50	% mol
Carbon dioxide	≤ 5	mg/ Sm ³
Sulphur from mercaptans (**)	≤ 6	mg/ Sm ³
Total sulphur (**)	≤ 20	mg/ Sm ³
Higher calorific value	34,95 ÷ 45,28	MJ/Sm ³
Wobbe index	47,31 ÷ 52,33	MJ/Sm ³
Relative density	0,555 ÷ 0,7	-
Dew point of water (to 7000 kPa relative pressure)	≤ -5	°C
Dew point of hydrocarbons (in the pressure range of 100 ÷ 7000 kPa relative)	≤ 0	°C
(*) for these components the acceptability values are intrinsically limited by the Wobbe index acceptability field		
(**) Excluding sulphur from odorising substances		

In June 2020, Snam introduced 10% of hydrogen into the network in the OroGiallo industry plant and they believe that the CO₂ emission will be reduced 5 million tons annually.

According to a Snam-McKinsey study, hydrogen could cover almost a quarter of national energy demand by 2050 in a 95% decarbonisation scenario, more than the current combined market share of electricity generated from renewable sources and fossil.

2.5.3 TRANSPORT OF LIQUEFIED HYDROGEN

Liquid hydrogen can be transported by road, ship, rail or in specific pipelines.

In the first three cases, double-walled cryogenic tanks with air vacuum are generally used to ensure maximum thermal insulation. Transport in liquid form is more efficient than in the form of compressed gas, especially in the case of large quantities. For example, 70 kg of liquid H₂ occupy a volume of 1000 litres and require containers with weights ranging from 200 kg to 300 kg to be transported. The same amount of hydrogen transported as compressed gas requires containers of up to 5 tonnes.



Figure 23 - Truck for liquefied hydrogen

As far as shipping is concerned, Canada has developed several projects for transoceanic hydrogen transport. One of these involves the use of 5 small barges carried in a larger ship that can be separated at the end of the journey. Each of them would carry 21200 kg of hydrogen without any loss during 50 days of travel.



Figure 24 - LNG ship

Liquid hydrogen can also be transported in specially constructed pipelines. This solution is only practicable if you have to cover small distances because the pipes must be insulated for the entire length in order to maintain the cryogenic temperatures required and prevent the formation of a two-phase flow (liquid/gas) explosion-prone.

2.5.4 COMPARISON BETWEEN DIFFERENT MODE OF TRANSPORT AND RELATIVE COST

The choice of mode of transport and distribution depends largely on the geographical spread and energy needs of the different users in terms of the flow of hydrogen transferred.

In the hypothesis of local consumption of medium/small size, the transport of hydrogen as compressed or liquified, appears as the economically and technically more appropriate solution.

Where large quantities of hydrogen need to be transferred over long distances, the most cost-effective method is based on pipelines, defined as hydrogen pipelines, which, after the investments necessary for their construction, require very low operating costs. This mode is convenient compared to the transport of liquid hydrogen that otherwise, not involving plant costs, is convenient in the case of transoceanic transport.

For small quantities of hydrogen, pipelines are not competitive, while in some cases compressed hydrogen may be the alternative to liquid hydrogen, whose operating costs are very high.

For example, if 100 tonnes per day (tpd), roughly the amount of hydrogen that would be required by a single 200 MW hydrogen power plant, are required at a location 500 km away from the point of import, then the use of trucks would be cheaper than constructing a pipeline; if 500 tpd are required, then a pipeline would have lower unit costs.

The transport of liquid hydrogen by land or sea is convenient when quantities are reduced and distances increase. The cost increase for liquefaction of gas is balanced by the better energy density that liquid hydrogen presents compared to compressed gas.

The only case in which the construction of pipelines could be preferred is that of the simultaneous distribution of electricity because they do not lead to significant energy losses caused by the transmission systems normally used.

In the Table 8 are reported the various transport costs of the different methodologies, for compressed and liquefied gas has been estimated a transported amount of 45800 GJ/year using tanks of capacity 21,72 GJ for compressed gas and 500 GJ for liquefied. Shipping is only dependent on the distance travelled as it is independent of the quantity transported.

Table 8 - Comparison of different transport method

Trip distance (Km)	COMPRESSED GAS		LIQUIEFIED GAS
	Truck (€/GJ)	Truck (€/GJ)	Ship (€/GJ)
16	4,20	0,21	-
161	9,40	0,50	-
322	16,30	0,90	11,90
805	36,60	1,80	12,70
1609	70,40	3,50	13,80

The Table 9 shows a comparison of estimated costs for the transport of compressed and liquefied hydrogen by rail.

Table 9 - Transport cost of hydrogen by rail

Transport Method Transport Time	Amount Transported (GJ/yr)	Specific TCI (€/GJ transported)	Transport Costs (€/GJ)	
Liquid Hydrogen	1 day (<984 km)	45600	9,80	1,90
		455600	3,90	1,15
		45,6 million	3,50	1,10
	2 days (<1970 km)	45600	9,80	1,90
		455600	5,90	1,40
		45,6 million	0,05	0,70
Compressed Hydrogen	1 day (<984 km)	45600	46,70	19,10
		455600	42,00	18,45
		45,6 million	42,00	18,45
	2 days (<1970 km)	45600	70,00	22,05
		455600	70,00	22,05
		45,6 million	70,00	22,05

2.6 APPLICATIONS OF HYDROGEN

Hydrogen is currently used mainly in the industrial field as a technical gas or as a process material. Today's world production is so used:

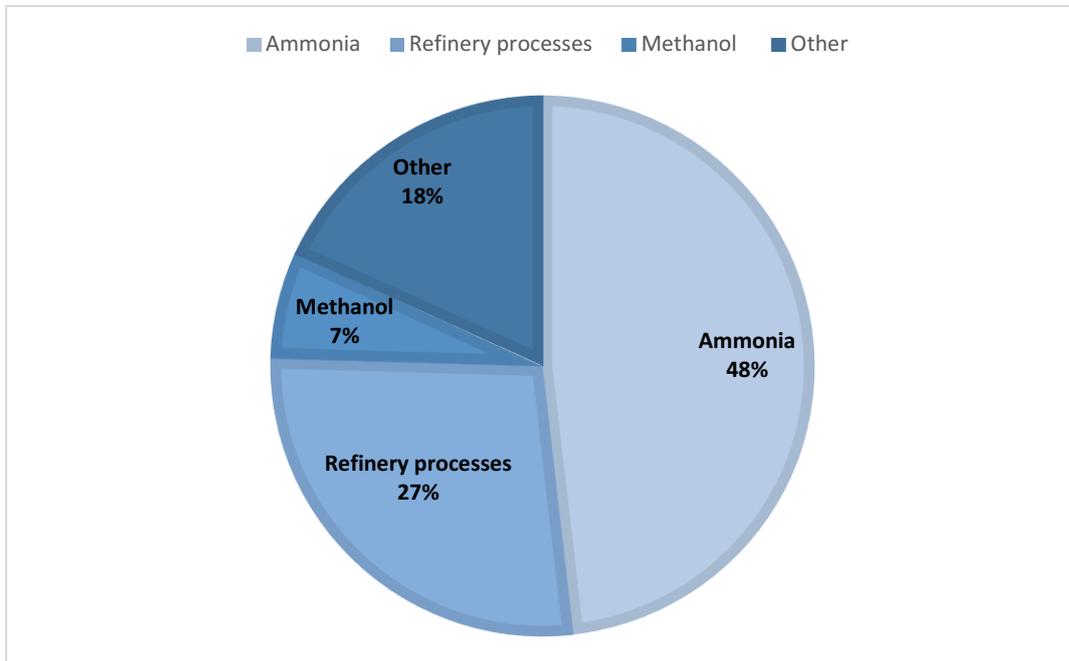


Figure 25 - Areas of application

The most important applications of hydrogen are:

- Food industry:
 - Hydrogenate liquid oils (such as soybean oil, fish, cotton seed oil and corn), transforming them into semi-solid materials such as fats, margarine and peanut butter.
- Chemical industry:
 - Manufacture of ammonia and methanol;
Ammonia (NH_3), used as fertilizer in agriculture, is produced through the Haber process, which allows industrial synthesis using as nitrogen and hydrogen reagents.
 - Hydrogenate inedible oils for soaps, insulation, plastics, ointments and other special chemicals.
- Production of metals:
 - Creating a protective atmosphere in high temperature operations such as stainless-steel manufacturing.

- Laboratory analysis;
- Metalworking:
 - Austenitic stainless welding, in Argon-based mixtures;
 - Support in plasma welding and cutting operations.
- Production of energy:
 - Heat transfer to cool turbine generators at high speed;
 - Oxygen reagent in boiling water-cooling plants for nuclear reactors to eliminate the incidence of intergranular corrosion cracking the cooling plant.
- Industry of glass:
 - For the production of float glass, hydrogen is used together with other industrial gases to obtain an induced atmosphere on the tin bath in order to prevent oxidation.
- Pharmaceuticals industry:
 - Production of sorbitol used in cosmetics, adhesives and vitamins A and C.
- Electronic industry:
 - To create specially controlled atmospheres in the production of semiconductor circuits.
- Aeronautics and Aerospace:
 - Used as an energy source, hydrogen is used as a fuel for rocket engines, providing energy to computers and life support systems in space.
- Automotive and transport:
 - As a component of heat treatment atmospheres, hydrogen reacts with any oxygen present, producing a brilliant finish on the steel parts;
 - It is used, either alone or in mixture with other gases, as quenching gas for high pressure quenching due to its high heat transfer properties;
 - When used as an alternative fuel in a fuel cell or directly in an internal combustion engine, hydrogen plays an important role in reducing unwanted emissions.
- Oil and gas industry:
 - To increase the performance of petroleum products.

CHAPTER 3

3 OXYGEN

In the previous chapter we treated the electrolysis of water, the two final products are hydrogen and oxygen. In this part, we will focus on the Oxygen compound.

3.1 THE DISCOVERY OF OXYGEN

Oxygen was discovered about 1772 by a Swedish chemist, Carl Wilhelm Scheele, who obtained it by heating potassium nitrate, mercuric oxide, and many other substances. An English chemist, Joseph Priestley, independently discovered oxygen in 1774 by the thermal decomposition of mercuric oxide and published his findings the same year, three years before Scheele published. In 1775–1780, French chemist, Antoine-Laurent Lavoisier interpreted the role of oxygen in respiration as well as combustion, discarding the phlogiston theory, which had been accepted up to that time; he noted its tendency to form acids by combining with many different substances and accordingly named the element oxygen (oxygène) from the Greek words for “acid former.”

3.2 CHEMICAL AND PHYSICAL CHARACTERISTICS OF OXYGEN

Oxygen, symbol O, is the eighth element in the periodic table, belonging to the VIB group of non-metals. Oxygen has atomic number 8, meaning it has 8 protons and 8 electrons; and its electronic configuration is $1s^2 2s^2 2p^4$.

This chemical element may be gaseous, solid and liquid; for the last two states of aggregation they are blue and are very paramagnetic.

Oxygen is one of the most common gases in the atmosphere. The air we breathe is composed of about 21% oxygen, 78% nitrogen and 1% other gases including argon and carbon dioxide. It is a colourless and odourless gas, in fact, for these characteristics it is impossible to detect an oxygen leak with the simple use of the senses.

Oxygen exists in three allotropic forms. Allotropes are forms of an element with different physical and chemical properties. The three allotropes of oxygen are normal oxygen, or diatomic oxygen, or dioxygen; nascent, atomic, or monatomic oxygen; and ozone, or triatomic oxygen. The three allotropes differ from each other in level of atoms and molecules. The oxygen that we are most familiar with in the atmosphere has two atoms in every molecule and the chemical formula is O_2 .

Monoatomic oxygen has only one atom per molecule. The formula is simply O, or sometimes (O). The parentheses indicate that nascent oxygen does not exist very long under normal conditions. It has a tendency to form dioxygen, that is the normal condition of oxygen at room temperature.

The third allotrope of oxygen, ozone, has three atoms in each molecule. The chemical formula is O_3 . Like nascent oxygen, ozone does not exist for very long under normal conditions. It tends to break down and form dioxygen. Ozone does occur in fairly large amounts under special conditions. For example, there is an unusually large amount of ozone in the Earth's upper atmosphere. That ozone layer is important to life on Earth. It shields out harmful radiation that comes from the Sun. Ozone is also sometimes found closer to the Earth's surface. It is produced when gasoline is burned in cars and trucks. It is part of the condition known as air pollution. Ozone at ground level is not helpful to life, and may cause health problems for plants, humans, and other animals.

In nature, oxygen consists of a mixture of three isotopes, ^{16}O , ^{17}O and ^{18}O ; in the atmosphere, ^{16}O predominates making up 99,76% of atmospheric oxygen, while ^{17}O has a percentage of 0,0374 and ^{18}O of 0,2039. There are also five radioactive isotopes of oxygen. A radioactive isotope is one that breaks down and emits some form of radiation. Radioactive isotopes are produced when very small particles are thrown onto atoms. These particles attach to atoms and make them radioactive. None of the radioactive oxygen isotopes have commercial use.

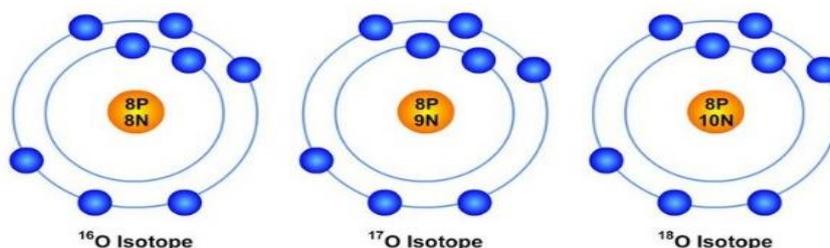


Figure 26 - Isotopes of oxygen

Oxygen is the essential element for many processes:

- respiratory processes of most living cells, such as photosynthesis;
- combustion processes.

Due to its electronegativity of 3,5 on the Pauling scale, oxygen reacts with almost all elements of the periodic table, except noble gases. The compounds that form are oxides, peroxides and hydroxides. The reaction capacity, or the level of oxidation, varies depending on the elements.

The main characteristics of oxygen are shown in the Table 10.

Table 10 – Physical - Chemical properties of oxygen

PHYSICAL – CHEMICAL PROPERTIES OF OXYGEN		
Property	Unit of measure	Value
Molecular weight	g/mol	15,999
Atomic radius	pm	60
Covalent radius	pm	73
Van der Waals radius	pm	152
Density of gas at 0°C	kg/m ³	1,429
Melting temperature	°C	-222,80
Boiling temperature at 1 atm	°C	-182,97
Critical temperature	°C	-118,55
Critical pressure	atm	49,84
Triple point at 151,99 Pa	°C	-218,787
Heat of fusion at -259°C	kJ/kg	13,9
Heat of vaporization at -253°C	kJ/kg	213,13
Thermal conductivity at 25°C	kJ/(kg°C)	0,02674
Viscosity at 25°C	Centipoise	0,0208
Heat capacity (Cp) of gas at 25°C	kJ/(kg°C)	0,921

3.3 PRODUCTION TECHNOLOGIES

The different oxygen production techniques differ mainly in the size of the plant, namely in the amount of oxygen produced per day, in the purity of the oxygen obtained and in the possibility of generating it in situ.

The production techniques are as follows:

- fractional distillation of air at low temperature;
- separation from air by adsorption on solids;
- separation from air with membranes;
- decomposition of oxides and salts;
- electrolysis of water (*discussed in the previous chapter*).

Nowadays, fractional distillation and electrolysis of water are the only techniques that can produce large quantities of oxygen of high purity. All other techniques are suitable to produce small and medium amounts of oxygen in situ, of not high purity, and have the advantage of being able to be put produced in a short time.

3.3.1 FRACTIONAL DISTILLATION OF AIR AT LOW TEMPERATURE

Oxygen can be obtained by liquefaction and fractional distillation of air, exploiting the diversity of the boiling points of its components that is nitrogen, oxygen and argon. In addition to these main components, CO₂ is present in the air and at lower concentration, the other noble gases like neon, helium, Krypton and xenon, also hydrogen and small amounts of methane CH₄, carbon monoxide CO, sulphur dioxide SO₂, nitrogen monoxide NO, ozone O₃, water H₂O.

In the cryogenic process, air is first liquefied at low temperature and then, through two distillation columns, the different components are separated. This technology is the one that currently provides the purest oxygen and is also the cheapest for medium and large-scale plants, that is for production over 200 t/day and up to 3000 t/day or for capacities from 8000 to 30000 Nm³/hour. In addition to oxygen, nitrogen and argon are also produced in the process. The oxygen obtained has a purity ranging from 95 to 99,90%.

The fractional distillation of air is divided in six stages.

In the first stage filtration and compression of air up to 65 bar are carried out, with subsequent cooling, usually at room temperature, and with the simultaneous elimination of a part of the water present. In a second stage, purification is carried out, to the complete elimination of water and CO₂ and of any other impurities present, such as hydrocarbons, which in the following stages, conducted at low temperature, would become solid with the risk for clogging the lines. Their elimination is achieved with two alternative technologies: adsorption on solids or condensation in reversible heat exchangers.

The third stage is heat exchange, which serves to cool the compressed air and heat the output products, thus recovering the refrigerators. The fourth stage is refrigeration, which is carried out by converting energy into work by expanding compressed gas into a turbine with lowering pressure and temperature.

The fifth stage is cryogenic distillation, conducted using two distillation columns showed in the Figure 27 to separate the air in the different products; the lower column operates at high pressure, the higher at low pressure. From the head of the first column, which operates at 6 bar, the liquid nitrogen comes out together with any volatile impurities such as hydrogen and helium, while from the bottom comes out liquid rich in oxygen with about 30-47%, which is sent to the second column, operating at atmospheric pressure. From this column pure liquid oxygen is recovered from the lower part and instead from the upper part nitrogen.

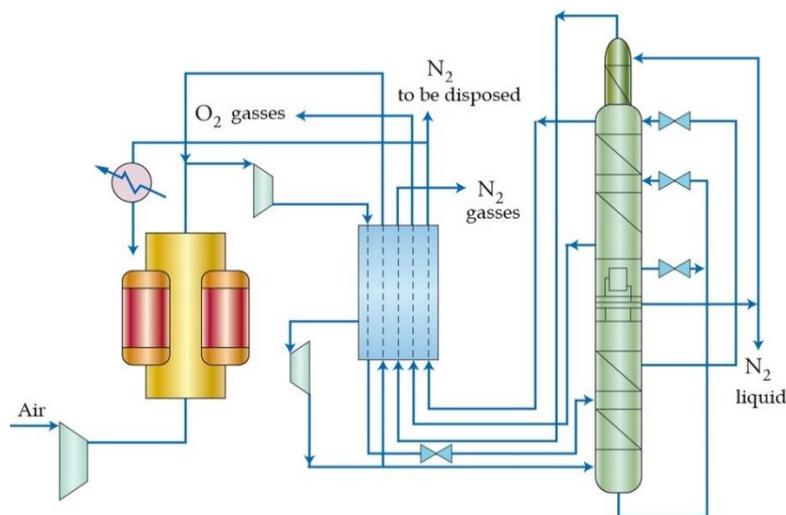


Figure 27 – Cryogenic distillation

The final stage is the recompression of the gaseous products obtained.

3.3.2 SEPARATION FROM AIR BY ADSORPTION

This technique aims to produce oxygen for water treatment and it is based on the use of adsorbent solids, zeolites, which have the property of retaining nitrogen and letting oxygen pass. Adsorption oxygen separation plants consist of three equal alumina containers, which are used to adsorb water and CO₂, and zeolite to adsorb nitrogen.

In each container, three phases are carried out:

1. Adsorption phase, in which air is introduced and oxygen comes out;
2. Decompression phase, which takes place when saturation is reached, that is when zeolite is no longer able to adsorb nitrogen, during which the adsorbed molecules come out and the material is regenerated;
3. Recompression stage to prepare the next phase of adsorption.

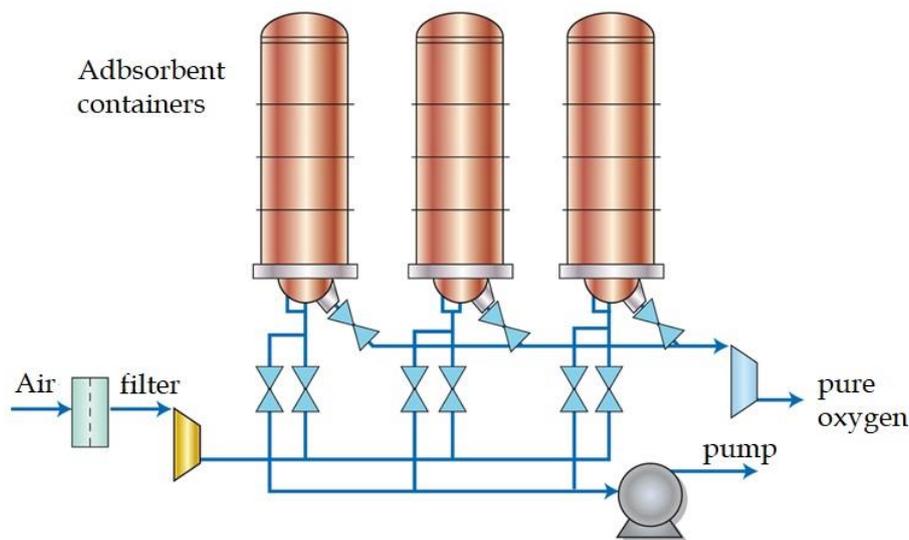


Figure 28 – Adsorption process

3.3.3 SEPARATION FROM AIR BY MEMBRANES

The principle of membrane separation is based on different rates of permeation of gases such as oxygen, carbon dioxide and water compared to nitrogen through special polymeric membranes.

The air flow passes inside a tube with walls made of a polymer membrane; oxygen, carbon dioxide and water pass quickly through the membrane, while nitrogen and argon, which are slower, escape from the tube in high concentrations.

With this technology, 50% oxygen is obtained in plants that can have a capacity of 1 to 500 t/day.

The membranes with the best performance are polymers derived from silicone rubbers. The advantage of using membranes is the ability to start the process immediately.

The use of this technology is currently very limited due to the low purity of the oxygen produced.

3.3.4 DECOMPOSITION OF OXIDES AND SALTS

Oxygen can be produced by decomposition of inorganic compounds such as chlorates, perchlorates, peroxides and superoxide. This technology is used for the production of oxygen in situ in breathing systems used, for example, in submarines, in planes in case of decompression, in bomb shelters and in emergency breathing systems.

The chlorates and perchlorates subjected to heating decompose releasing oxygen.

3.4 STORAGE AND TRANSPORT OF OXYGEN

Oxygen is often stored as a liquid, although it is used primarily as a gas. Liquid storage is less bulky and less costly than the equivalent capacity of high-pressure gaseous storage.

Oxygen is supplied with pipelines, tanks or cryogenic trucks and in situ production. Currently 40% of oxygen is distributed by pipeline, 44% with cryogenic plants in situ, 10% in the liquid state with wagons or cryogenic trucks, 5% produced in situ with non-cryogenic plants and 1% in the gaseous state in cylinders.

Oxygen tanks containing pressures up to 200 bar are used for industrial processes including the manufacture of steel, welding and cutting, medical breathing gas, diving and as emergency backup in aircraft.

3.5 APPLICATION OF OXYGEN

Both liquid and gaseous oxygen are used in different sectors such as:

- Food and beverage industry:
 - For packaging in a protective atmosphere;
 - For the oxygenation of fish farms;
 - As ozone, for disinfection and sterilization in industrial processing.
- Chemical industry:
 - Pure oxygen is used in the production of numerous chemicals, such as ethylene oxide and titanium dioxide. It is also used to increase the production capacity of many oxidation processes;
 - To increase the capacity and destruction efficiency of waste incinerators.
- Mechanical engineering:
 - Combined with fuel (e.g. acetylene) for both conventional and laser cutting.
- Paper:
 - Allows to comply with the strict environmental regulations applicable to delignification processes, oxidative extraction and waste water treatment.
- Research:
 - Used in the research centres, universities, schools;
- Refining:
 - To reduce viscosity and improve the flow in oil and gas wells;
 - Used to increase the capacity of FCC (Fluid Catalytic Cracking) and SRU (Sulfur Recovery Units) plants and to improve wastewater treatment operations;
 - To reduce sulphur emissions from refineries.
- Energy:
 - For high efficiency combustion generators;
 - Used in boilers and process heaters, industrial fermenters and gasification processes to improve productivity.

- Health:
 - For resuscitation or, in combination with other gases, for anaesthesia;
 - Treatment of respiratory failure and resuscitation, hospitals, and laboratories.
- Pharmaceuticals and biotechnology:
 - Essential in cell growth applications, oxygen is used in fermenters and bioreactors.
- Semiconductors and electrotechnics:
 - ultra-pure, oxidation of certain materials, neon production;
- Iron and steel:
 - To create a hot flame in the high temperature welding torches used in cutting and welding;
 - To support oxyfuel cutting operations;
 - Decarburization of iron for steel production and air enrichment of blast furnaces, foundries.
- Aerospace:
 - For the launch of numerous spacecraft;
 - To fuel the combustion of the propellants used for rocket engines.
- Glass:
 - To increase combustion in glass furnaces and reduce No_x emissions.;
 - For ecological fusion of glass.
- Environmental treatment:
 - Waste and drinking water treatment; incineration of waste.
- Fish farming and underwater fishing:
 - For the maintenance of fish fauna and for underwater fishing activities of diving centres.
- Textile and tanning:
 - For water treatment.

3.6 REGULATION FOR THE USE OF TECHNICAL GASES OXYGEN AND HYDROGEN

The reference standards that indicate the minimum pureness of gases, the quality and the analytical methods are the Farmacopea Europea as regards the use in the medical and pharmaceutical field.

Oxygen must respect the parameters represented in the Table 11 in the medical field.

Table 11 - Oxygen parameter

Parameter	Unit of measure	Value
Purity	%	99,50
CO	ppm	< 5
CO ₂	ppm	< 300
Water vapour	ppm	< 67

The standard for the use in the food field for gas food additives is Reg. 231/2012 and the standard qualities are showed in the Table 12.

Table 12 - Oxygen and Hydrogen parameters in food field

	OXYGEN	HYDROGEN
EINECS	231-956-9	215-605-7
Purity	≥ 99 %	≥ 99,90 %
Water	< 0,05 %	< 0,05 % v/v
Methane and other hydrocarbons	< 100 µl/l	-
Nitrogen	-	< 0,07 % v/v
Oxygen	-	< 0,001 % v/v

As for the use in other fields there is no specific legislation; the purity depends on the user who chooses it based on the use that must do; for example, the electronics industry requires a very high purity of gases compared to a use such as conventional welding.

CHAPTER 4

4 MARKET ANALYSIS

Market analysis were carried out to obtain an overview of the users of hydrogen and oxygen technical gases in the Marche region and in the North of Abruzzo region, analysing the suppliers, their costs and the average annual quantities used.

This market analysis was carried out with the aim of identifying the appropriate location of a pilot plant for the production of hydrogen and oxygen from a renewable source, namely solar energy.

As for hydrogen, being still an innovative technology, today, hydrogen consumption in Marche Region is limited to feedstock uses in refining, the only user is the API oil refinery located in Falconara Marittima.

Italiana Petroli S.p.A., also known as API Group, is an Italian private company active in the field of fuels and mobility services, dealing with the refining and distribution of refined petroleum products, manages the entire oil cycle of the "downstream", from crude oil supply, to refining, logistics to distribution and sale.

API Group purchases two types of hydrogen from SOL, a company specialized in the production and marketing of technical, industrial, pure and special and medicinal gases. The hydrogen purchased is:

- Ultra-pure hydrogen in 50 l cylinders used for laboratory analysis.
The price for ultra-pure hydrogen in a cylinder is 6,30 €/m³ therefore the cost of a cylinder is 63,50 €/each.
- Compressed Hydrogen on a cylinder carriage containing 20 of 50-litre cylinders used for starting hydrogen production plants.
Each 50-litre cylinder develops 10 m³ of hydrogen at room temperature.
The price for compressed hydrogen in the tank is 1,80 €/m³ therefore the cost of a tank is 360 €/each.

In addition, the API in the refinery has two Hydrogen production plants with a capacity of 5500 and 8500 Nm³/h. The average annual production is about 120 million m³ per year.

The cost of production is approximately 0,10 €/m³, including the cost of electricity necessary for the operation of pumps and compressors of the plants themselves and the cost of methane used both as fuel for reaction furnaces and as a raw material for the extraction of hydrogen. Currently the cost of methane is about 230 €/tonne.

A summary scheme is shown in the Table 13.

Table 13 - Hydrogen users in Marche Region

COMPANY	LOCATION	GAS	PRICE €/m ³	SUPPLIER	AVERAGE ANNUAL QUANTITY
API	Ancona (AN)	Ultra pure Hydrogen	6,30 m ³	SOL (Ancona)	1041 m ³
		Compressed Hydrogen	1,80 m ³	SOL (Ancona)	41000 m ³
		Self- produced Hydrogen	0,10 m ³	API	120 million of m ³

Refining plants follow a Distillation-Vacuum reforming-Visbreaking cycle, which can treat crudes in a wide quality range.

Hydrogen production is based on the steam reforming process in the presence of high temperature water vapor as described in Section 2.3.1. The plants are powered by natural gas. To the charge gas is added a stream of pure hydrogen, necessary to transform any presence of mercaptans in hydrogen sulphide in the reactor Sulphur absorber. To the charge gas at the outlet of the reactor is added the water vapour necessary to the reactions of steam reforming and the mixture is preheated in the convection of the furnace at the expense of the combustible gases. At this point the mixture enters the adiabatic reactor pre-reformer in which, in the presence of the catalyst, the reactions of hydrocarbons with water begin to take place which give rise to the formation of hydrogen, carbon monoxide and carbon dioxide.

At the exit of the reactor, the mixtures of hydrogen, water vapour, hydrocarbons, carbon monoxide and carbon dioxide are sent to the catalytic reforming section. The outgoing gas consists mainly of hydrogen, water and non-reactive hydrocarbons, carbon monoxide and carbon dioxide. This gas is cooled in the waste heat boiler where high pressure water vapor is generated and in the boiler feed water preheater before reaching the MT shift converter reactor. In this reactor, filled with catalyst, the reactions of carbon monoxide with water are completed, which give rise to the formation of further hydrogen and carbon dioxide. The reaction is exothermic. At the outlet, the gas preheats the boiler feed water in the two heat exchangers before being cooled in the air and water coolers.

At the outlet of this exchanger there are two phases: *a steam*, saturated with water, consisting mainly of hydrogen, methane, carbon monoxide and carbon dioxide and *a liquid*, consisting of water with traces of carbon monoxide and carbon dioxide. The aqueous phase is sent to the condensed recovery system. The vapour phase is sent to the absorption system on molecular sieves consisting of four receptacles filled by the sieves and one receptacle for the equalisation of the purge gas pressure. The molecular sieve system produces a hydrogen current with a purity of more than 99,90% by volume that is sent into the network. The gas from the equalisation vessel consisting of methane, hydrogen, carbon monoxide and carbon dioxide is sent to the furnace burners. These burners are special burners with low pressure and low CO and No_x development.

Hydrogen is used in refining processes to eliminate polluting compounds such as sulphur and nitrogen from fuels, which leads, both on a global and local scale, to lower pollutant emissions from the use of fuels, petrol and diesel, with a lower sulphur content.

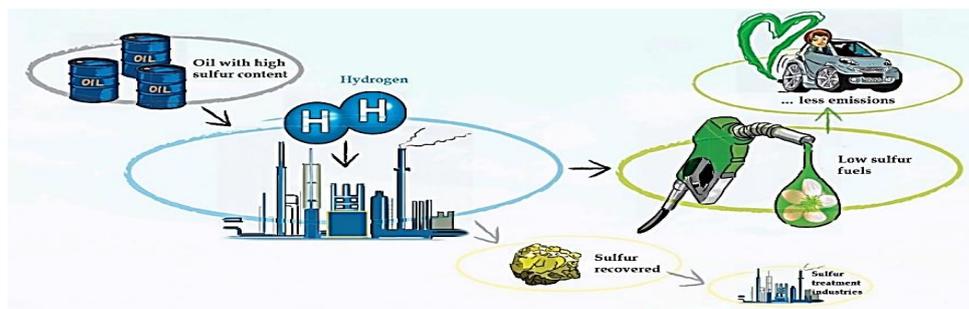


Figure 29 - Use of Hydrogen in refining process

For the market analysis conducted for Oxygen, this technical gas is widely used mainly in the metallurgical sector. The Table 14 shows the users, the purchase price, the supplier and the average annual quantity used in Marche Region.

With the orange colour are highlighted companies in the metallurgical sector.

Table 14 - Oxygen users in Marche Region

COMPANY	LOCATION	GAS	PRICE €/m ³	SUPPLIER AND LOCATION	AVERAGE ANNUAL QUANTITY
AMA ENGINEERING	Maltignano (AP)	Oxygen	0,20 m ³	SAPIO (Fermo)	21 m ³
TA. G METALLI	Ascoli Piceno (AP)	Oxygen	0,81 m ³	Nippon Gases	2040 m ³
DECAMEC srl	Ascoli Piceno (AP)	Oxygen	0,75 m ³	Nippon Gases	3 tanks of 8,80 m ³
CIARROCCHI SILVIO snc	Ascoli Piceno (AP)	Oxygen	3,50 m ³	SOL (Ancona)	350 m ³
DINDI srl	Belvedere Ostrense (AN)	Oxygen	0,56 m ³	Gas Tecnici Foligno (PG)	7200 m ³
ASG srl	Ancona (AN)	Oxygen	3,27 m ³	SOL (Ancona)	2 tanks of 8,80 m ³
OMAS spa	Numana (AN)	Oxygen	0,163 m ³	SOL (Ancona)	29500 m ³
METAL ART	Senigallia (AN)	Oxygen	0,429 m ³	SOL (Ancona)	10800 m ³
METALDESI	Fabriano (AN)	Oxygen	3,00 m ³	SOL (Ancona)	3 tanks of 8,80 m ³
FUSTELLIFICIO P.M. srl	Corridonia (MC)	Oxygen	0,28 m ³	SIAD (Ancona)	4000 m ³
ST JAMES PHARMACY	Monteprandone (AP)	Oxygen Medical use	0,17 litre	LINDE MEDICALI (Fermo)	144 tanks of 3000 litres

The Table 15 shows the users, the purchase price, the supplier and the average annual quantity used in Abruzzo Region.

Table 15 - Oxygen users in North Abruzzo Region

COMPANY	LOCATION	GAS	PRICE €	SUPPLIER	AVERAGE ANNUAL QUANTITY
METAL TECNO SRL	Martinsicuro (TE)	Oxygen	2,76 m ³	AIR LIQUIDE ITALIA SERVICE SRL <u>(Porto Recanati)</u>	13606 m ³
COMAP srl	Corropoli (TE)	Oxygen	4,55 m ³	UNIWELD <u>(Centobuchi)</u>	3 tanks of 8,80 m ³
CARAFÀ E MARRA srl	Arielli (CH)	Oxygen	3,98 m ³	NIPPON GASSES (Val di sangro)	2 tanks of 8,75 m ³
NEW GENERAL IMPIANTI srls	Pescara (PE)	Oxygen	3,20 per litres	C.O.A. (CENTRO OSSIGENO ABRUZZESE) (Ortona)	8 litres
FARMACIA NENNA	Orsogna (CH)	Oxygen Medical use	0,0059 per litre	DOMOLIFE (Pescara)	432.000 litres

The first two companies of the Abruzzo Region are supplied from producers of oxygen localized in the Marche Region.

This analysis shows that the most strategic point for the location of a hydrogen and oxygen plant is **Ancona**, as most of the companies analysed are supplied in this area.

5 HYDROGEN AND OXYGEN POWER PLANT

To date, the hydrogen and oxygen market is still difficult to estimate because it is expanding and still suffering from so much uncertainty. Anyway, on the basis of the technology review, a rough estimation of H₂-O₂ production plant main technical features can be performed. For this study, a modular approach was chosen.

A basic “module” for the contemporary production of hydrogen and oxygen with a purity grade up to 5 or 5,5, including supply water treatment (demineralization) and having an electrical power of 2,50 MW could be considered.

Main technical features of the module are listed below.

- Electrical Power 2,50 MW;
- Efficiency about 75%;
- H₂ flow rate 360 Nm³/h up to a purity grade 5/5,5;
- O₂ flow rate 180 Nm³/h up to a purity grade 5/5,5;
- Water consumption 1,24 l/Nm³ H₂;
- Water treatment up to a purity grade ASTM II included;
- Component in containerized execution
- Physical dimensions about 900 m² - no 10 containers:
 - no 4 containers (40') 12x3x3 meters for electrolyzers;
 - no 1 container (40') 12x3x3 meters for water and gas treatment;
 - no 1 container (40') 12x3x3 meters for air compression;
 - no 1 container (40') 12x3x3 meters for hydrogen compression;
 - no 1 container (40') 12x3x3 meters for oxygen compression;
 - no 1 container (40') 12x3x3 meters for hydrogen storage at 300 bar;
 - no 1 container (40') 12x3x3 meters for oxygen storage at 300 bar;
- Operational hours at full power (2,5 MW) 2500 h/year;
- Energy consumption (supplied by PV) 6250 MWh/year;
- Energy supplied by the RTN negligible for economic reasons;
- Operating life 20000-40000 hours (8-16 years);
- Maintenance operation interval 2000 hours.

Connecting in parallel several modules higher volume rates of gas could be obtained. Anyway, surface footprint, water and electricity consumptions will increase linearly with the assumptions made, producing technical constraints.

The system would consist of a total of 10 containers, which could be placed on a square area of 30 m side, for a total of 900 m² like in the Figure 29.



Figure 30 - Layout modules

The proposed plant has a higher producibility than that currently required on the market, but since it is a market currently growing, it has been specifically chosen to provide for a greater production of oxygen and hydrogen to meet future market demands.

The proposed plant uses water from the water supply both for cooling machinery, both for the production of demineralized water for electrolysis.

The water flow rate varies depending on the gas production. At the maximum rate of production, the module will consume about 277 l/h of demineralized water.

Demineralised water production is already included in the plant proposed and will require about 0,70 m³/h.

In case of lack of connection to the water line, the system can be cooled air and the water needed for the electrolysis system can be recovered with an air humidity extraction system. As for the purification of water, this modular system includes a reverse osmosis system and double filtration with micro-pellets of active resins capable of reaching an ASTM II degree.

5.1 INTERNATIONAL STANDARDS

Two main international standards are applicable to the activities of hydrogen production and handling:

- **ISO 22734-1 2008:** Hydrogen generators using water electrolysis process Part 1: Industrial and commercial applications. This standard defines the construction, safety and performance requirements of packaged or factory-matched hydrogen gas generation appliances, herein referred to as hydrogen generators, using electrochemical reactions to electrolyse water to produce hydrogen and oxygen gas. It is applicable to hydrogen generators intended for indoor and outdoor commercial and industrial use (non-residential use). Hydrogen generators that can also be used to generate electricity such as reversible fuel cells are excluded from the scope of this International Standard.
- **ISO/TR 15916:2004:** Basic considerations for the safety of hydrogen systems. This standard provides guidelines for the use of hydrogen in its gaseous and liquid forms. It identifies the basic safety concerns and risks, and describes the properties of hydrogen that are relevant to safety. Detailed safety requirements associated with specific hydrogen applications are treated in separate International Standards.

Many other existing standards considered hydrogen as a fuel for vehicles and are not applicable at the project analysed in this study.

Some other standards are under development by the ISO technical committee ISO/TC 197 *“Hydrogen Technologies”*. In particular, the standard ISO/WD 19884 *“Gaseous hydrogen — Cylinders and tubes for stationary storage”*, will be the reference standard for stationary storage of H₂.

Dealing with safety of hydrogen production storage and transportation, we mention the ATEX directives *“Protection of employees from explosion risks”* 99/92/EC ATEX 137A and 94/9/EC ATEX 100.

5.2 SAFETY REGULATIONS

A regulation about safety in flammable gasses production compression and storage exists in Italy and has to be considered in each installation. Two decrees are applicable in this sector:

- **Presidential Decree (DPR) 105/2015:** fulfilment of EU 2012/18/UE directive, related to the danger of significant accident due to dangerous substances.
- **Presidential Decree (DPR) 151/2011:** simplification of fire prevention regulation in fulfilment of article 49, clause 4-quarter of decree no. 78 dated 31/05/2010.

DPR 105/2015, also known as **SEVESO III** directive, provides dispositions in order to avoid significant accidents due to some dangerous substances, limiting consequences for human health and environment.

Hydrogen production and storage facilities in which the quantity of gas is higher than 5 tons, are subjected to the provisions of this decree.

Taking into account H₂ gas density, at atmospheric pressure and 0 °C, SEVESO III directive is applicable to industrial activities containing more than 55'617 Nm³ of H₂. This condition essentially excludes the projects involved in this study from the application of this directive.

DPR 151/2011 highlights activities subjected to fire prevention controls, defining projects filing, projects examinations, technical site visit, exceptions to specific rules and verifying of the fire safety conditions. National Fire Department is in charge of all these activities.

The following industrial activities are interested by fire prevention inspections:

- Facilities and plants where flammable gasses are produced or used in quantities higher than 25 Nm³/h;
- Plants for compression and expansion of flammable gasses with a flow rate higher than 50 Nm³/h;
- Storage of flammable compressible gasses in fixed tanks with total volume equal or higher to 0,75 m³.

On the basis of the provisions of DPR 151/2011, it is highly probable that the projects involved in our study will be activities interested by fire prevention inspections.

Even if there is not a specific regulatory framework dealing with hydrogen, a useful regulation reference to be used in designing hydrogen storage is Ministerial Decree dated 23 October 2018 *“Technical rule of fire prevention for design, construction and operation of hydrogen distribution facilities for automotive applications”*.

Most of the significant barriers to the H₂ plant diffusion has been largely overcome thank to a very important and effective work among the Fire Department, Ministries, the Italian Association for Hydrogen and Fuel Cell and several interested stockholders, introducing an innovative approach where the perspective analysis has been supported by risk analysis. Thus, the current decree allows the use of pressures, now common, up to 700 bar, and guarantees better alignment with ISO 19880.

Storage installations compliant with technical standard *“ISO/FDIS 19884 Gaseous hydrogen — Cylinders and tubes for stationary storage”* are considered by the decree as *“state of the art installations”*.

5.3 PERMITTING FOR H₂ PRODUCTION AND STORAGE

The production of hydrogen, in Italy, is regarded as an industrial activity, irrespective of the production method, even when produced from non-emitting methods such as water electrolysis. Hence, such activity would only be permitted in an area designated as an industrial zone or, under specific conditions, in commercial areas. The permitting process for building and operating a hydrogen production facility are officially treated on a uniform basis throughout Italy

In accordance with Annex VIII-Second Part of decree 152/2006, Hydrogen production is subject to the *“Integrated Environmental Authorization (AIA)”*.

The AIA is the measure that authorizes the operation of an industrial activity and defines the conditions for the compliance with IPPC requirements (integrated pollution prevention and reduction).

The competent authority is the Ministry for Environment, Land and sea protection (MATTM) - Directorate for sustainable growth and quality of development (CreSS).

Applications can be submitted for the following cases:

- AIA for new installation
- AIA for existing installation
- AIA review
- AIA for substantial amendment
- AIA update for non-substantial amendment

The AIA procedure includes the following phases:

1. Submission of the application which includes the description of:
 - Type of activity and production;
 - Raw material;
 - Installation site;
 - Waste disposal;
 - Dangerous emissions.
2. Preliminary verification of the applications completeness within 30 days;
3. Starting of the procedure which includes:
 - Definition of the responsible for the procedure;
 - Communication and publication on the website.
 - Submission of comments on the application to the Competent Authority within 30 days from the date of publication on the website
 - Request for integrations within 30 days from of the request.
4. Technical preliminary investigation
 - Steering committee, the competent authority may request integrations to the documentation indicating the maximum deadline cannot exceeding 90 days.
 - Definition of the procedure for which the competent authority expresses its evaluation within 150 days from the submission of the application.
5. Closing of the procedure.

The applicant needs to accurately describe the destination and scope of the plant to be installed so that the municipal authorities can assess compatibility with the Land Use Plan.

Then, the local Fire Department is responsible for providing an evaluation in terms of safety and fire prevention, based on which the permission is given to operate the plant.

5.3.1 LAND USE PLAN

As said before, the hydrogen production facility must be located in an area where “industrial” or “commercial” activities are permitted according to the local Land Use Plan (Piano Regolatore).

There are no specific requirements, except for the need to notify the intervention to the Fire Department.

The plant area should be defined as ATEX area (ATEX Directive 2014/34/EU).

In case of storage, the stored quantities of H₂ have to be accurately determined and communicated to the Fire Department.

Three classes of storage with different requirement (according with the decree DPR 151/2011) are defined:

- less than 0,75 m³ (up to 1000 bar);
- less than 10 m³ (up to 1000 bar);
- more than 10 m³ (up to 1000 bar).

Different classes have different risks and hence different requirements have to be respected.

5.3.2 PERMITTING REQUIREMENTS

The main requirements with their applicable regulations for hydrogen production facility construction (e.g. permitting regime, agreement) are the following:

- a) Environmental impact according to the national specifications;
- b) Risk assessment: Fire Department will assess risks submitted by the director of operations for construction/installation and based on the technical features of the plant;
- c) Safety requirements and safety distances: assessed by Fire Department according to Ministerial Decree 23 October 2018 and SEVESO III directive (adopted in Italy as DPR 105/2015) if applicable.

5.4 GRID CONNECTION OF HYDROGEN PTG PLANT

According to the ARERA resolution 574/2014/R/EEL “Regulations concerning the integration of electrical energy storage systems in the national electrical system”, a power to gas plant would be considered, if existing, as a plant powered by non-renewable energy, or, if not yet existing, the procedural and economic conditions designed for high efficiency cogeneration plants will be applied.

From the technical point of view the permitting framework is defined by ARERA resolutions ARG/elt 281/5 (2005), ARG/elt 99/08 (2008), 226/2012/R/eel (2012) and 328/2012/R/eel (2012).

There are no specific laws for regulations for Power to Gas plants; their legal status is the same as any other industrial plant.

5.5 PERMITTING PROCEDURES FOR H₂ INJECTION INTO THE GAS GRID

The injection of hydrogen into the gas grid, whether for Power to Gas (P₂G), energy storage, or other purposes, can be done at two levels:

1. At the Transmission Service Operator (TSO) level, where the TSO is typically responsible for managing and maintaining the national high pressure, long distance, gas grid ‘trunking’ network and provides the network interface with any international gas grid connections and local distribution network connections;
2. At the Distribution Service Operator (DSO), level, where the DSO is typically responsible for managing and maintaining the local, regional, low pressure gas grid network and provides the network interface with those seeking to establish gas injection facilities and those seeking gas offtake facilities.

Gas injection composition levels for TSO and DSO networks are also set by mandated limits within regulatory frameworks for operation, safety or other conventions, and 100% hydrogen is not allowed in any instance.

Moreover, the Italian regulations have not set any defined limit yet. The only standard is the Gas Grid Code of Snam Rete Gas, where provisions concerning the qualitative characteristics of the gas injected into the grid include the allowed presence of

hydrogen, but only with reference to bio methane fed to the grid. In this case the maximum allowed concentration of hydrogen in bio–methane minor or equal to 0,50% by volume, Annex 11/A of the Grid Code.

There is no regulation on remunerations, related to the injection of hydrogen into gas network as for example connection costs, feed–in tariffs.

5.6 PERMITTING PROCEDURES IN TRANSPORTATION OF H₂

The Ministry of Infrastructure and Transport Decree dated 12 May 2017 (National transposition of the European Agreement concerning the International Carriage of Dangerous Goods by Road: DIR/2016/2309/EC - ADR 2017) provides rules for transport of hydrogen, related to:

- the classification of dangerous goods for the purpose of road transport
- the shipping procedures (labelling, marking documentation)
- the use of packaging and tanks
- the dispositions related to construction
- the test and approval of packaging and tanks
- the use and requirements of means of transport
- the cases of exemption.

Though the rules for hydrogen transport are slightly different from those involving other types of gas, there are no specific types of roads or special routes for hydrogen transport, since hydrogen is considered as any other dangerous good and the rules for its transport are those defined by the ADR. The authorities in charge to allocate specific routes are local Authorities (Regional and Municipalities) in agreement with the Fire Department, with the approval of the Ministry of Infrastructure and Transport.

ADR has also included the requirement for hydrogen transport regarding tunnels, bridges and parking. It requires tunnels to be classified according to risk.

The transport of dangerous goods is allowed without restrictions for category A tunnels. For example, if hydrogen is transported in tanks, there are restrictions for tunnels of the categories B, C, D and E, whereas hydrogen transport in other containers is not allowed in tunnel categories D and E.

5.7 ANALYSIS OF WATER AVAILABILITY

Water is strictly necessary for the production of green hydrogen by electrolysis. As reported above in this study, a volumetric rate of about 990 l/h of water is needed to produce 1000 Nm³/h or 90 kg of H₂ (at atmospheric pressure), having an installed electric power of 4,20 MW for the alkaline electrolyser. As a rule of thumb, about 1 l/h of water for the production of 1,30 Nm³/h of H₂ (and 0,65 Nm³/h of O₂) is required. A demineralization treatment for supplying water is also needed. The water treatment section is usually included in the electrolyser auxiliary equipment. Purity grade required for water is possibly ASTM II (maximum conductivity equal to 1 μS/cm at 25 °C).

5.7.1 REGULATORY FRAMEWORK FOR WATER SUPPLYING

Water supply in Italy is regulated by a local operator which defines the standards for the connection and supply. The regulations for water supply and connection to the water pipeline in the Marche Region are briefly described below.

5.7.2 ANCONA PROVINCE WATER SUPPLY REGULATION

The pilot plant will be located in Ancona, in the Marche Region, where Viva Servizi S.p.A is the company in charge of management and maintenance of the water pipeline. This company has issued a regulation for water supply and connection to the water pipeline.

According to this, water supply is subject to the existence of a standard connection or to the construction of a new one. In order to obtain a connection to the pipeline, the applicant must:

- Submit a regular application to the Operator;
- Pay the connection costs.

The service can be provided, with the authorization of the Municipality, in the areas not covered by water network yet.

In these cases, the authorized applicant can realize the connection pipeline at its own cost, and the connection has to be realized in compliance with Annex A of the regulation.

6 RENEWABLE ENERGIES

“Only if our generation believes it is the only owner and beneficiary of the planet's exhaustible energy resources, can it continue on this path. If, on the other hand, he believes he has a responsibility towards future generations, he must recognize that the time has come to change direction.”

Vincenzo Balzani, “Energia per l’astronave terra”

Today, the production of electricity is one of the main causes of air pollution. Producing electricity by continuing to use traditional fossil sources means polluting air, water and land. Instead, the great opportunity offered by renewables, allows you to produce electricity in a clean way, reducing the impacts of activities and helping to protect the environment.

Renewable energy is defined as *“any energy source that regenerates at least at the same rate as it is used”*. It is energy derived from natural resources that replenish themselves in less than a human lifetime without depleting the planet’s resources. In agreement with the International Energy Agency (IEA) the classification of main renewables energies is:

- 1) Hydroelectric power;
- 2) Solar energy;
- 3) Wind energy;
- 4) Biomass energy;
- 5) Geothermal energy;
- 6) Marine energy.

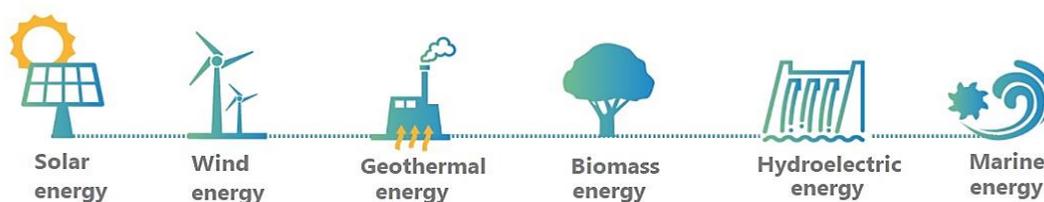


Figure 31 - Renewable energies

These resources, such as sunlight, wind, rain, tides, waves, biomass and thermal energy stored in the earth's crust, are available in one form or another nearly everywhere. They are virtually inexhaustible. And, what is even more important, they cause little climate or environmental damage.

Fossil fuels such as oil, coal, and natural gas on the contrary are available in finite quantities only. As we keep extracting them, they will run out sooner or later. Although produced in natural processes, fossil fuels do not replenish as quickly as we humans use them.

The main uses of renewable energies are presented in Table 16.

Table 16 - Renewable energies and their use

Energy sources	Energy conversion and usage options
Solar	Solar home systems, solar dryers, solar cookers
Direct solar	Photovoltaic, thermal power generation, water heaters
Wind	Power generation, wind generators, windmills, water pump
Geothermal	Urban heating, power generation, hydrothermal, hot dry rock
Biomass	Heat and power generation, pyrolysis, gasification, digestion
Hydropower	Power generation
Wave and tide	Numerous designs, barrage, tidal stream

Renewable sources have many advantages, but there are also some limits, such as: discontinuity of generation due to seasonal variations; sometimes the sun is missing, sometimes the wind is missing, sometimes both, it is a situation that the Germans call "*Dunkelflaute*". As long as the renewables cover a limited amount of the overall electricity generation this is not a big problem, it will become when instead they will be predominant so their exploitation requires a complex design, planning and control optimization methods. There will also need more solar panels and wind turbines than normally required, will also need different storage methods and all this will involve higher costs; but the continuous technological advances are allowing to manage these optimization difficulties, one of these solutions will be *hydrogen*.

In this elaboration, we will focus on solar energy, since one of the best ways to produce *green hydrogen* is through the use of photovoltaic panels.

6.1 EVOLUTION OF RENEWABLE ENERGIES AND THEIR COSTS

Electricity costs from renewables have fallen sharply over the past decade, driven by improving technologies, economies of scale, increasingly competitive supply chains and growing developer experience. Power generation from renewable sources and technologies has become increasingly competitive with, or indeed, less costly than, fossil-based or nuclear power. In 2000 the price of renewables was forty times higher than that of oil. Today, it is estimated that it will become competitive with some current fuels within five years. With or without the health and economic crisis, coal plants were overdue to be consigned to the past.

Demand for solar PV is spreading and expanding as it becomes the most competitive option for electricity generation in a growing number of locations, for residential and commercial applications and increasingly for utility-scale projects. PV increases at a much faster rate than wind energy, about 25% a year and in 2050 it will become the most important source of energy for mankind. PV is indeed an ideal source of energy: it converts sunlight into electricity with 20% efficiency (100 times more than natural photosynthesis), it can be used everywhere, it is scalable, long lasting, cheap and reliable.

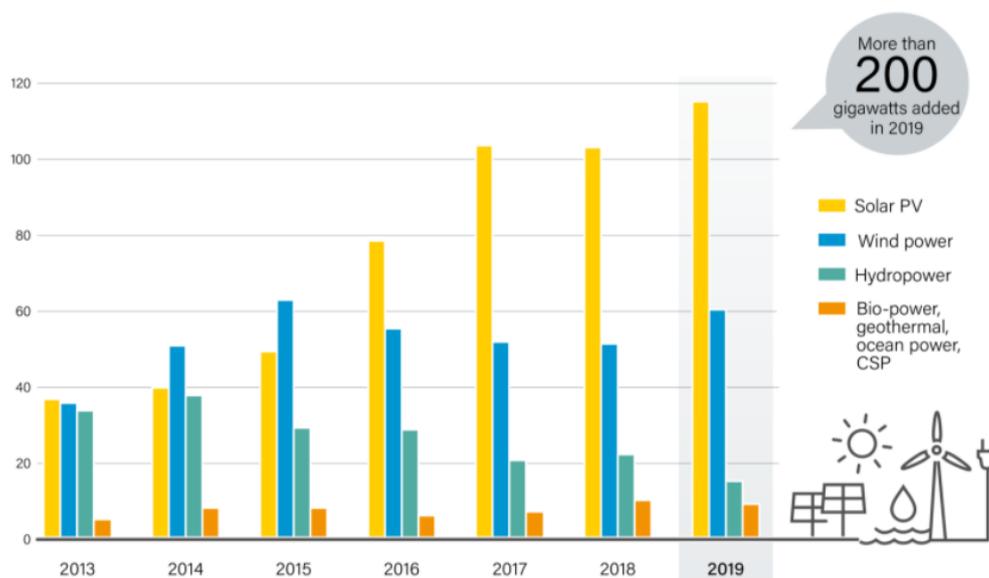


Figure 32 - Evolution of renewable energies

Since 2011, renewable energy is growing faster than all other energy forms. More than 200 GW of new renewable power generating capacity was installed in 2019, raising the global total to 2,588 GW by year's end.

Around 115 GW of solar PV was added worldwide in 2019, cementing the technology's status as the leader in new electricity generating capacity. During the year, 57% of renewable power capacity additions were of solar PV (direct current), followed by wind power, about around 60 GW for 30% and hydropower, about some 16 GW for 8%. The remaining 5% of additions were from bio-power, geothermal power and concentrating solar thermal power (CSP).

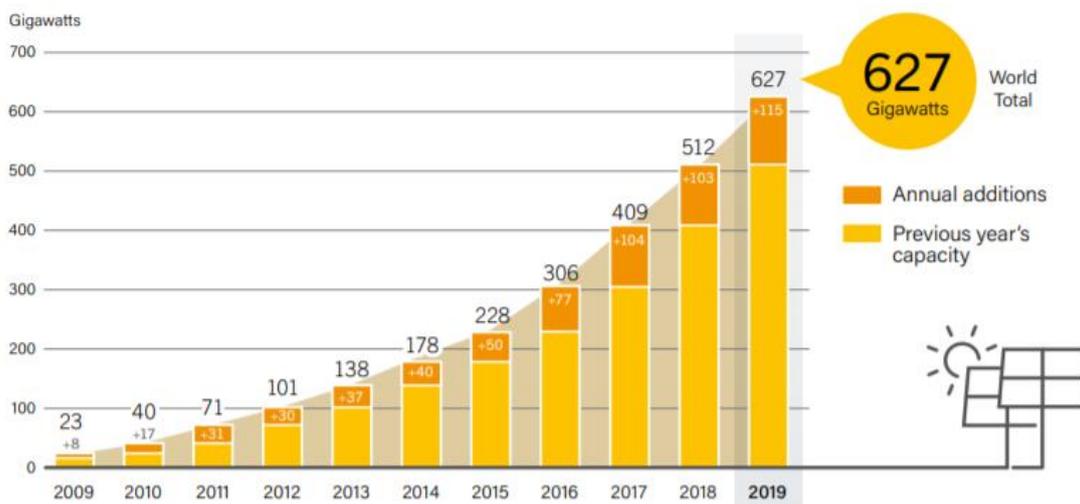


Figure 33 – Increasing of solar PV technologies

Costs for solar and wind power technologies continued to fall year on year.

Electricity costs from utility-scale solar PV fell 13% in 2019, reaching a global average of USD 0,068 per kilowatt-hour (kWh). Onshore and offshore wind both declined about 9%, reaching USD 0,053/kWh and USD 0,115/kWh, respectively.

According to International Renewable Energy Agency (IRENA), recent auctions and power purchase agreements (PPA) show that the trend will continue for new projects commissioned in 2020 and beyond: "Solar PV prices based on competitive procurement could reach an average of USD 0,039/kWh for projects commissioned in 2021, down 42% compared to 2019 and over a fifth less than the cheaper fossil fuel competitor, or coal-fired power stations".

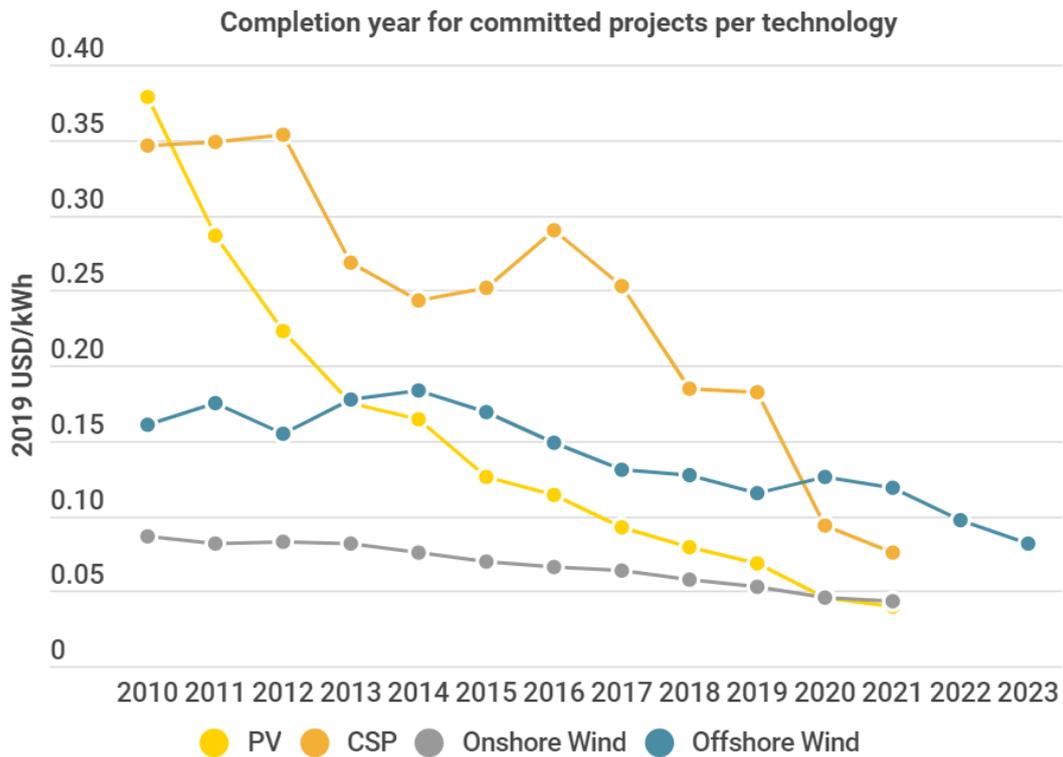


Figure 34 - Falling of the cost for solar and wind energy

IRENA’s annual report shall also examine the value of the investment in relation to the decrease in generation costs. The same amount of money invested today in renewable energy produces more new capacity than it would have had a decade ago. In 2019, twice as much renewable energy generation capacity was commissioned as in 2010, but required only 18% more investment.

6.2 EVOLUTION OF THE COST OF GREEN HYDROGEN

The main factors on which the decrease in the cost of green hydrogen is based are three: the cost of renewable sources that, as we explained before, is in rapid decline, that of capital and that of electrolyzers.

The forecast for hydrogen from low-cost wind and solar PV projects is expected to achieve competitiveness with fossil fuels within the next five years. Instead for the fossil fuels with Carbon Capture and Storage, costs are expected to remain generally unchanged. Cost of hydrogen from SMR are expected to increase by 2% on average from 2025 to 2040. For advanced natural gas reforming, costs would increase by 13%, while for hydrogen from coal gasification, costs would decrease by 11%.

The figure 35 shows the trend of hydrogen production costs from solar and wind in comparison with fossil fuels.

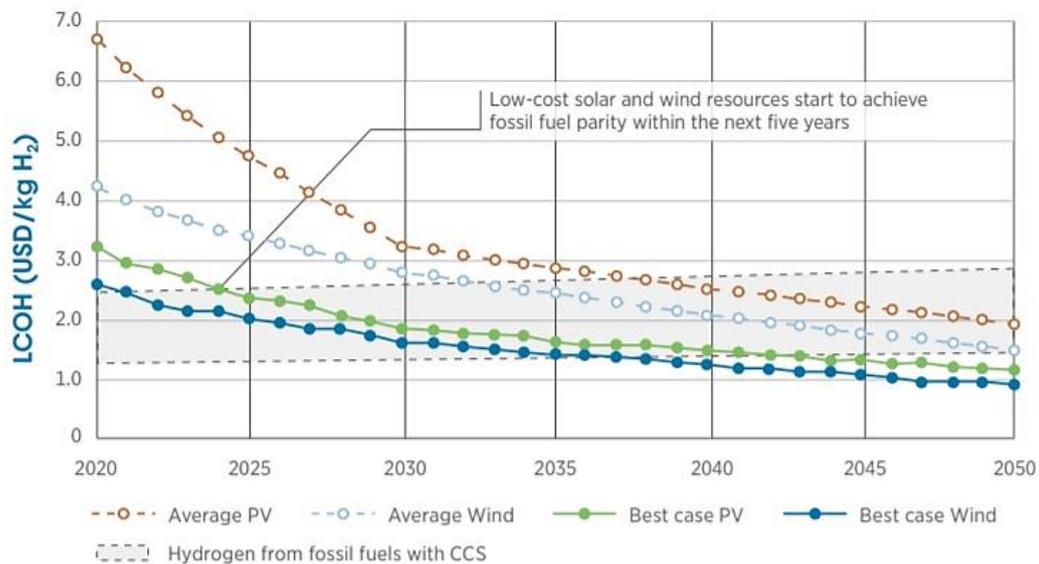


Figure 35 - Hydrogen production costs from solar and wind vs. fossil fuels

The total capacity of the electrolyzers installed globally in 2019 is very low, around 150 megawatts. The potential for increasing volumes and reducing the cost curve is enormous. About that, it should be considered that currently about 40% of the price of the electrolyzers reflects the cost of the raw material, mainly represented by pre-assembled parts. With the increase of the production the volume of transactions of the suppliers along the chain of the value will increase also, reducing the cost of the finished product. The increase in demand will therefore support the design and production of larger, higher power plants, which will help to further reduce costs.

Electrolyser costs should halve from 840 USD/kW to 375 USD/kW between now and 2050. Based on these elements, it is estimated that the construction of about 20 gigawatts of electrolysis capacity in the next five years would allow to bring the cost of green hydrogen to a competitive level in many applications.

Over the decade, it would take to reach 50 gigawatts to reach below the turning point of 2 dollars per kilogram in Italy and in many areas of the world.

6.3 SOLAR ENERGY

Among renewable energy sources, the sun has a fundamental role because it is at the base of the origin of all the energy sources on earth: renewable and non-renewable resources. The Sun radiates our planet for a power of about 180 thousand billion kilowatts. Some of the sun's rays are reflected from the Earth's atmosphere to outer space. At any time, the Sun radiates an energy equivalent to 1367 Watts / m². Overall, it reaches the Earth's surface about 1 kilowatt of solar energy per square meter.

As it passes through the atmosphere, the solar radiation attenuates because it is partly reflected and absorbed, especially by water vapor, ozone, oxygen, carbon monoxide. The radiation that reaches the Earth's surface in a straight line is called direct radiation (Gb) while the radiation dispersed by the air and particles suspended in it, which still manages to reach the Earth, affecting with various angles, is called diffuse radiation (Gd). There is also a further component of radiation called albedo (Ga), generally of modest size and due to reflection with other surfaces like land, ponds, adjacent buildings.

The intensity of solar radiation on the ground depends on the angle of inclination of the radiation itself on a horizontal surface: the smaller the absolute value of the angle, the greater the thickness of the atmosphere it has to pass through, the smaller the radiation that reaches the surface. Direct radiation affects any surface with a well-defined angle, while diffuse radiation affects the same surface with many angles. This phenomenon is very important because photovoltaic panels work even in the presence of the only diffuse component. Moreover, an inclined surface, such as that of photovoltaic panels, can also receive reflected solar radiation. The need to distinguish between direct, diffuse and reflected solar radiation arises from the fact that the panels do not respond equally when struck in proportions other than the three components.

Solar energy can be converted:

- DIRECTLY: photovoltaic conversion, thermal conversion, thermo-electric conversion through concentration panels;
- INDIRECTLY: wind energy, biomass, wave motion, etc.

There are three main solar energy technologies:

- Photovoltaic solar panel converts solar energy directly into electricity through the help of the physical properties of some semiconductors. Electrons in these materials are freed by solar energy and can be induced to travel through an electrical circuit, powering electrical devices or sending electricity to the grid;
- Solar thermal panel (or solar collector) is a technology capable of capturing the thermal energy of the sun's rays and use this heat to provide hot water, space heating, cooling, and pool heating for residential, commercial, and industrial applications. These technologies displace the need to use electricity or natural gas;
- Concentrating solar panel captures the sun's rays by means of a system of parabolic mirrors with a linear structure that concentrate them towards a single point where a thermo-vector fluid flows or towards a boiler.

In function of the different storage systems photovoltaic systems are classified in two different types: grid-connected or utility-interactive systems and stand-alone systems. The plants connected to the network provide the interconnection of the plant to the national or local electricity network; those stand-alone are designed to remain precisely isolated, and are carried out in particular situations where the connection to the electricity grid is impossible or at least too expensive. Networked plants are more flexible, and less expensive than stand-alone ones, because they do not require the purchase of accumulators to store the electricity produced and not consumed.

6.3.1 PV POWER PLANT COMPONENTS

The main components of a PV power plant include:

- Solar PV modules: These convert solar radiation directly into electricity through the photovoltaic effect in a silent and clean process that requires no moving parts. The PV effect is a semiconductor effect whereby solar radiation falling onto the semiconductor PV cells generates electron movement. The output from a solar PV cell is DC electricity. A PV power plant contains many cells connected together in modules and many modules connected together in strings to produce the required DC power output.

PV cell technologies can be crystalline or thin-film. Crystalline silicon cells provide high efficiency modules and can be mono-crystalline silicon (mono-c-Si) or multi-crystalline silicon (multi-c-Si). Mono-c-Si cells are generally the most efficient, but are also more costly than multi-c-Si. Thin-film cells provide a cheaper alternative, but are less efficient. There are three main types of thin-film cells: Cadmium Telluride (CdTe), Copper Indium (Gallium) Di-Selenide (CIGS/CIS), and Amorphous Silicon (a-Si).

- Inverters: These are required to convert the DC electricity to alternating current (AC) for connection to the utility grid. Many modules in series strings and parallel strings are connected to the inverters.
- Module mounting (or tracking) systems: These allow PV modules to be securely attached to the ground at a fixed tilt angle, or on sun-tracking frames.
- Step-up transformers: The output from the inverters generally requires a further step-up in voltage to reach the AC grid voltage level. The step-up transformer takes the output from the inverters to the required grid voltage.
- The grid connection interface: This is where the electricity is exported into the grid network. The substation will also have the required grid interface switchgear such as circuit breakers (CBs) and disconnects for protection and isolation of the PV power plant, as well as metering equipment. The substation and metering point are often external to the PV power plant boundary and are typically located on the network operator's property.

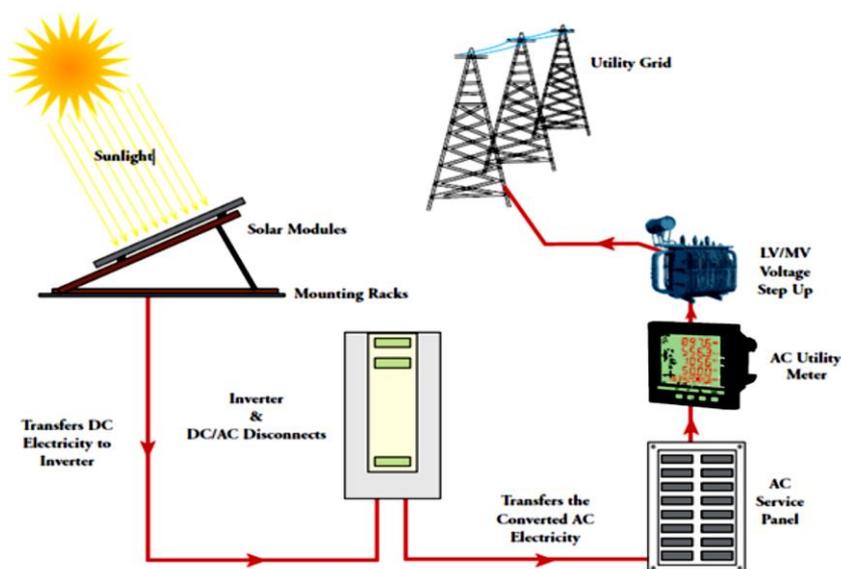


Figure 36 - Components of PV power plants

6.4 CASE OF STUDY: PV POWER PLANT

As we have already explained in the previous chapter, the purpose of this work is study is the study of a plant for the production of hydrogen and oxygen by electrolysis of water and the electrolyser will be powered by a photovoltaic system. In this section, we will explain in detail the characteristics of the photovoltaic system taken into consideration.

The photovoltaic system under study is installed on the ground in Barcaglione village, in the Municipality of Falconara Marittima, in the Province of Ancona, in the Marche Region. The area has a slope between 6 and 24 degrees, with an orientation varying from the North West and South.

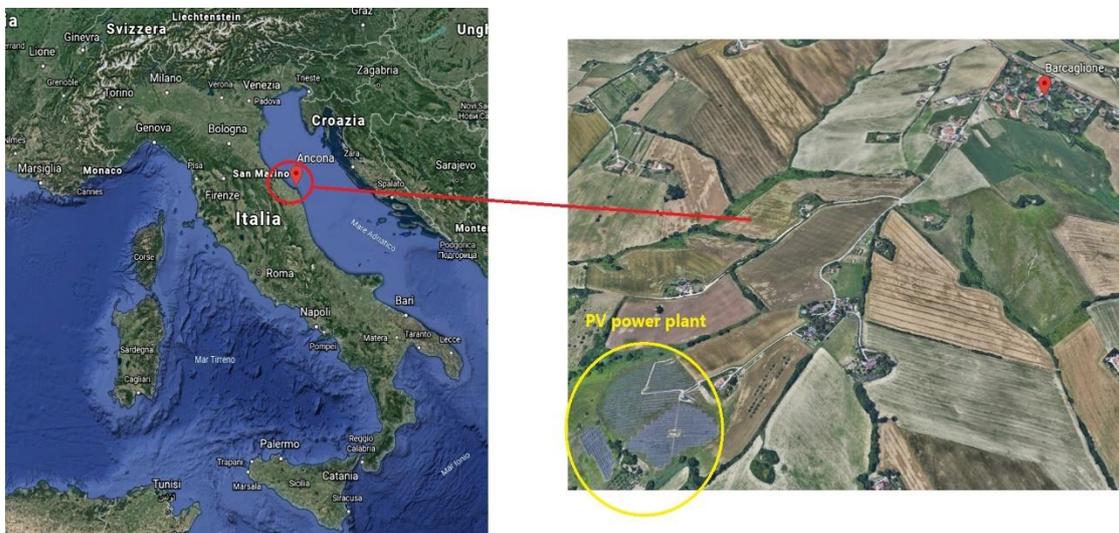


Figure 37 - Localization of the PV power plant

The photovoltaic field is composed of 15296 photovoltaic panels with a nominal power of 210 W produced by SunPower. SunPower is a leading company in the photovoltaic sector and in the production of photovoltaic panels since 1985.

The plant occupies an area of 56000 square meters. The structures are oriented at 19 °C towards the South and inclined at 25 °C in the Northwest and 30 °C in the Southeast, at an inter-distance from pole to pole equal to 8,00 m in the North West and 4,70 m in the South East.

From the point of view of the electrical connection of the modules and strings with the conversion equipment, the system is designed according to the multi string inverter configuration.

In a multi-inverter system, the field is divided into several parts, called subfields, each served by its own inverter, with the advantage of reducing the problems of shading or different exposure between the strings, provided that strings with identical modules and homogeneous exposure conditions are combined in the same subfield.

Given that the photovoltaic field is able to generate a total rated power of 3212,16 kWp in STC conditions and the static converters have a rated output voltage of 400V - 3F - 50 Hz, for interfacing to the M.V. network at 20 kV, two 1000 kVA power transformers incorporated in resin are used, with primary at 400 V and secondary at 20 kV Dyn11 vector group and short-circuit voltage of 6% and two 800 kVA power transformers incorporated in resin, with primary at 400 V and secondary at 20 kV Dyn11 vector group and short-circuit voltage of 6%.

The layout consists of six prefabricated self-supporting monobloc type electric field cabins in AC, divided into inverter room, LV panel room and transformer room, and four substations divided in ENEL room, measurement room and MV user room, Trafo and LV panel room, Inverter room. The Figure 38 shows the layout of the PV plant.

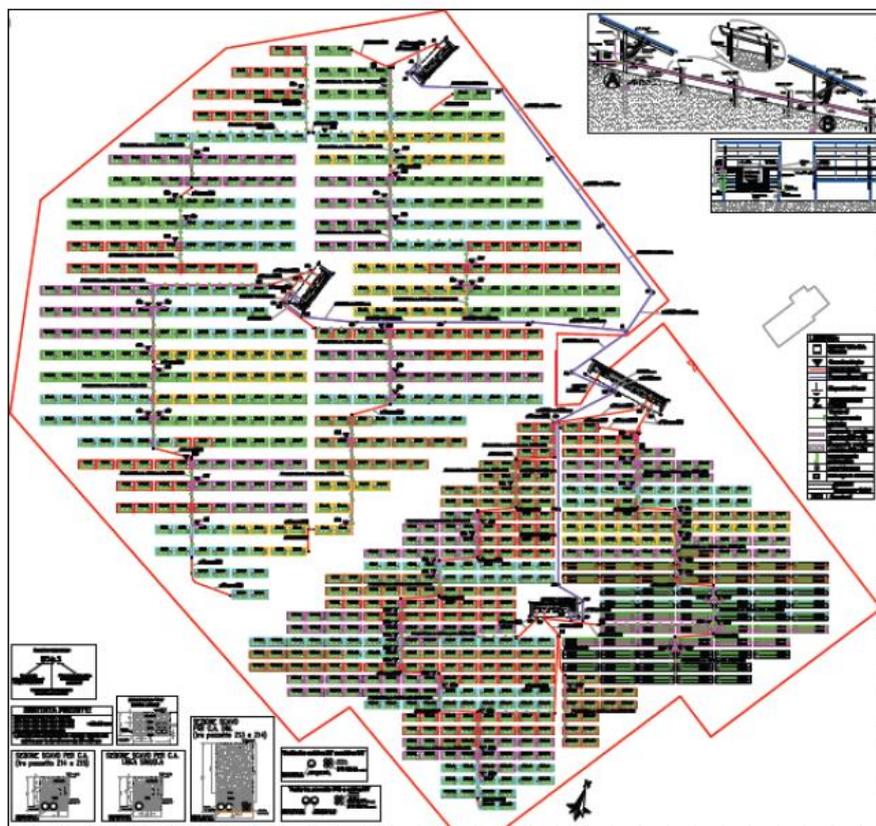


Figure 38 - Layout of the PV power plant

The main technical characteristics of the photovoltaic modules are shown in the Table 17.

Table 17 - Characteristics of PV modules

Characteristics of photovoltaic modules	
Producer	SUNPOWER
Model	210
Rated power	210 Wp
Efficiency on the module	16,90 %
Type of cell	Monocrystalline silicon
Tension MPP	40 V
Current MPP	5,25 V
Open circuit voltage	47,7 V
Short circuit current	5,75 V
Maximum system voltage	1000 V
Temperature coefficient Isc	3,50 mA/K
Temperature coefficient Voc	-136,8 mV/k
Temperature coefficient Pmax:	-0,38 %/K
Module length	1,559 mm
Width of the module	798 mm
Depth of module	46 mm
Module weight	15,0 kg
Power guarantee	25 years
Warranty on the product	10 years



Power-one inverters were used, of which number 2 of PVI-330.0-IT and number 12 of PVI-220.0-IT. Table 18 summarizes the characteristics of the two inverters.

Table 18 - Inverter characteristics

Inverter characteristics		
Producer	POWER-ONE	
Model	PVI-330.0 – IT	PVI -220.0-IT
Rated power DC	338,4 kW	225,6 kW
Maximum DC power output	354 kW	236 kW
Maximum DC current	738 A	492 A
MPPT voltage range	485-850 V	485-850 V
Rated current AC	486 A	324 A
Rated power AC	330 kW	220 kW
Rated voltage AC	400 V	400 V
Yield Euro	95,5%	95,3%
Degree of protection environmental	IP20	IP20
Size	1250x2116x893,5 mm	1250x2116x893,5 mm
Weight	1,700 kg	1,300 kg
		

6.4.1 RADIATION AND ENERGY PRODUCIBILITY

Irradiation analyses and predictions were conducted using the international weather database called PV-Gis, based on climate data normalized on a European basis and available within the European Solar Radiation Atlas.

The model algorithm estimates global irradiance/irradiance on horizontal or inclined surfaces.

The results of the processing using PV-Gis are:

- North West Area - inclination 25 °C, orientation 19 °C S,
Daily irradiance equal to 1630 kWh/m²; specific producibility equal to 1260 kWh/kW per year;
- South East Area - inclination 30 °C, orientation 19 °C S,
Daily irradiance equal to 1640 kWh/m²; specific producibility equal to 1270 kWh/kW year.

These values assume an ideal situation of total absence of shading; it has been estimated therefore a loss of production of the plant in about 5 % compared to the condition of absence of shading. The calculated specific producibility values are:

- North West Area - inclination 25°, orientation 19, S: 1209 kWh/kW per year
- South East Area - inclination 30°, orientation 19, S: 1168 kWh/kW per year

Finally, the total specific producibility is 1188,5 kWh/kW per year and the total annual producibility is 3803,2 MWh / year.

6.5 BUSINESS PLAN

To complete the assessment, a technical-economic analysis was drawn up in order to validate the real feasibility of the plants by analysing three different cases:

1. **SCENARIO 1**: Construction of the hydrogen and oxygen plant connected to an existing photovoltaic system;
2. **SCENARIO 2**: Construction of the hydrogen and oxygen plant connected to a new photovoltaic system;
3. **SCENARIO 3**: Construction of the hydrogen and oxygen plant powered by an electricity taken from the grid.

6.6 SCENARIO 1

It is assumed to realize the hydrogen and oxygen plant in the existing photovoltaic system described in the Section 6.4. The economic assessment will therefore not take into account the costs of construction the photovoltaic system but will take into account the cost of energy to be paid to the owner of the PV plant. The components and the characteristics of the H₂-O₂ have been described in the Section 5. Since the electrolyser consumes an energy of 6250 MWh/year, and the photovoltaic plant studied has a producibility of 3800 MWh/year, the missing energy to power the H₂-O₂ power plant will be taken directly from the electricity grid.

Before starting the economic analysis, the two parameters that are important for this study will be introduced.

- The first is called **CAPEX** (Capital Expenditure), to indicate the initial economic investment that includes all the costs relating to the design and construction of the plant studied;
- The second is called **OPEX** (Operating Expense) and considers the management and the annual maintenance of the equipment that make up this plant.

These two parameters will be the starting points of the analysis and will be fundamental for the understanding of the economic feasibility of the plant.

6.6.1 CAPEX SCENARIO 1

The values presented were obtained following a survey by specialized suppliers in the energy sector. In the Table 19 all the costs are summarized to obtain the total CAPEX related to the power plant in question. The final value is equal to 7.085.000,00 €.

Table 19- CAPEX H₂-O₂ power plant

CAPEX ASSUMPTIONS	
Containers cost	5.450.000 €
Design, Authorization and other costs (15 % of containers cost)	817.500 €
Transportation, Civil and Electrical works (15 % of containers cost)	817.500 €
TOTAL CAPEX	7.085.000 €

6.6.2 OPEX SCENARIO 1

With regard to OPEX, that is the factor that contains all the costs related to the maintenance and management of the power plant, the relative costs will be considered:

- Water supply, considering a water consumption of the electrolyser of 300 m³ per year and a water supply cost of 3,60 euros per m³;
- Operation and maintenance O&M, valued at 5% of the cost of the containers;
- Cost of energy taken from the grid, the price of electricity is summarized in the Table 20 and are based on PUN (Prezzo Unico Nazionale) is the reference price of electricity recorded on the Italian Power Exchange. At this initial price, 150 €/MWh were added to obtain the final price of energy to power the electrolyser taking into account the costs of system charges, taxes, expenses for transport and management.
- Cost of energy to be paid to the owner of the photovoltaic system. The price of electricity captured by photovoltaic power plant are summarize in the Table 20. At this initial price, after an agreement with the owner of the photovoltaic system, 10 €/MWh were added to obtain the final price of energy to power the electrolyser.

Table 20 - Price of electricity captured by PV

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
YEAR	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
€/MWh	49,59	52,94	55,04	56,90	59,71	62,41	64,86	67,63	70,73	69,82	69,44	69,84	69,51	69,06	68,51

In order to make correct the economic analysis, each value must be considered, calculated in each year of operation of the plant until the end of its life, in this case 15 years; considering 2021 as zero year in which only the initial cost of the plant was incurred.

In the Table 21 all the costs are summarized to obtain the total OPEX for different years.

Table 21 - OPEX H₂-O₂ power plant

YEAR	OPEX WATER SUPPLY €/year	OPEX O&M €/year	OPEX ENERGY COST PV €/year	OPEX ENERGY COST GRID €/year	TOTAL OPEX €/year
2021	0,00	0,00	0,00	0,00	0,00
2022	10.800	275.500	226.445,06	488.997,47	1.001.742,54
2023	10.800	275.500	239.167,29	497.199,97	1.022.667,26
2024	10.800	275.500	247.170,13	502.359,69	1.035.829,82
2025	10.800	275.500	254.211,56	506.899,56	1.047.411,11
2026	10.800	275.500	264.912,56	513.798,89	1.065.011,44
2027	10.800	275.500	275.155,69	520.403,01	1.081.858,71
2028	10.800	275.500	284.486,88	526.419,17	1.097.206,05
2029	10.800	275.500	294.981,69	533.185,56	1.114.467,25
2030	10.800	275.500	306.755,10	540.776,31	1.133.831,41
2031	10.800	275.500	303.303,43	538.550,89	1.128.154,32
2032	10.800	275.500	301.861,12	537.620,99	1.125.782,11
2033	10.800	275.500	303.380,67	538.600,70	1.128.281,37
2034	10.800	275.500	302.148,37	537.806,19	1.126.254,56
2035	10.800	275.500	300.427,46	536.696,65	1.123.424,11
2036	10.800	275.500	298.325,68	535.341,56	1.119.967,24

6.6.3 ECONOMIC RESULTS SCENARIO 1

From the market analyses carried out and from the various studies, a sale price for hydrogen was estimated at 1,50 €/Nm³ and a price for oxygen of 3,00 €/Nm³.

Considering the power plant studied, with a production of respectively of 900.000 Nm³/year of hydrogen and 450.000 Nm³/year of oxygen, the revenues per year are showed in the Table 22:

Table 22 – Revenues H₂-O₂

Revenues		
Revenues due to H ₂ production	1.350.000	€/year
Revenues due to O ₂ production	1.350.000	€/year

A degradation coefficient of 0,50 %/year has been estimated, so the revenues over the years will be:

Table 23 - Total Revenues

YEAR	RENEUVES H ₂	REVENUES O ₂	TOT REVENUES
2021	0,00 €	0,00 €	0,00 €
2022	1.350.000,00 €	1.350.000,00 €	2.700.000,00 €
2023	1.343.250,00 €	1.343.250,00 €	2.686.500,00 €
2024	1.336.533,75 €	1.336.533,75 €	2.673.067,50 €
2025	1.329.851,08 €	1.329.851,08 €	2.659.702,16 €
2026	1.323.201,83 €	1.323.201,83 €	2.646.403,65 €
2027	1.316.585,82 €	1.316.585,82 €	2.633.171,63 €
2028	1.310.002,89 €	1.310.002,89 €	2.620.005,78 €
2029	1.303.452,87 €	1.303.452,87 €	2.606.905,75 €
2030	1.296.935,61 €	1.296.935,61 €	2.593.871,22 €
2031	1.290.450,93 €	1.290.450,93 €	2.580.901,86 €
2032	1.283.998,68 €	1.283.998,68 €	2.567.997,35 €
2033	1.277.578,68 €	1.277.578,68 €	2.555.157,37 €
2034	1.271.190,79 €	1.271.190,79 €	2.542.381,58 €
2035	1.264.834,84 €	1.264.834,84 €	2.529.669,67 €
2036	1.258.510,66 €	1.258.510,66 €	2.517.021,32 €

As mentioned, the term of any feasibility study must have a precise economic analysis to fully understand the real convenience of a given investment. Keeping in mind the two values already presented, CAPEX and OPEX, the EBITDA index is first introduced, defined as Earnings Before Interest, Taxes, Depreciation and Amortization, i.e. the cash flow obtained by the company without consider interest, taxes, depreciation and amortization. The value is obtained simply by making the algebraic difference between revenues, obtained from the sale, and annual expenses, OPEX.

$$EBITDA = REVENUES - OPEX$$

In the Table 24 are summarized all the values obtained for the different years.

Table 24 - EBITDA

YEAR	EBITDA
2021	-7.085.000,00 €
2022	1.698.257,46 €
2023	1.663.832,74 €
2024	1.637.237,68 €
2025	1.612.291,05 €
2026	1.581.392,21 €
2027	1.551.312,93 €
2028	1.522.799,72 €
2029	1.492.438,49 €
2030	1.460.039,81 €
2031	1.452.747,54 €
2032	1.442.215,24 €
2033	1.426.876,00 €
2034	1.416.127,02 €
2035	1.406.245,56 €
2036	1.397.054,09 €

Also, the depreciation coefficient has to be considered. Depreciation is defined as an "economic-accounting procedure that provides for the distribution of the cost of an instrumental asset, for several years, as many as in relation to a particular percentage, defined as 'depreciation coefficient'".

In this case the coefficient is equal to 9 % /year, so for a certain number of years the cost of the power plant is deducted from the business income with shares equal to 9% of its value. So, the H₂-O₂ power plant will be deductible from the company's income for about 11 years with quotas of 637.650,00 euros per year.

It is also necessary to introduce taxes, which are considered to be 24 % of EBITDA and the depreciation ratio. Cash flow is calculated to obtain the profit entering the company's coffers every year and are summarized in the Table 25.

$$NET\ CASHFLOW = EBITDA - TAXES$$

Table 25 - Net Cash Flow

YEAR	NET CASH FLOW
2021	-7.085.000,00 €
2022	1.443.711,67 €
2023	1.417.548,88 €
2024	1.397.336,64 €
2025	1.378.377,20 €
2026	1.354.894,08 €
2027	1.332.033,82 €
2028	1.310.363,79 €
2029	1.287.289,26 €
2030	1.262.666,26 €
2031	1.257.124,13 €
2032	1.249.119,58 €
2033	1.084.425,76 €
2034	1.076.256,53 €
2035	1.068.746,62 €
2036	1.061.761,10 €

Finally, the Cumulated Cash Flow will be calculated, which indicates how much money has to enter the investor's coffers in order to be repaid of the initial CAPEX and is calculated by adding every year the cash flow to the CAPEX considered negative. The final value of Cumulated Cash Flow, if positive, indicates the final gain obtainable from the investment.

Table 26 - Cumulated Cash Flow

YEAR	CUMULATED CASH FLOW
2021	-7.085.000,00 €
2022	-5.641.288,33 €
2023	-4.223.739,44 €
2024	-2.826.402,81 €
2025	-1.448.025,61 €
2026	-93.131,53 €
2027	1.238.902,29 €
2028	2.549.266,08 €
2029	3.836.555,34 €
2030	5.099.221,59 €
2031	6.356.345,72 €
2032	7.605.465,30 €
2033	8.689.891,06 €
2034	9.766.147,60 €
2035	10.834.894,22 €
2036	11.896.655,32 €

From graph 39, it can be seen that from the year 2027 the value will turn positive.



Figure 39 - Cumulative Cash Flow Scenario 1

In order to assess the economic feasibility of an investment, the three main indicators have been considered:

- **NPV** (Net Present Value): value given by the algebraic sum of cash flows, suitably brought back to a reference time, through the mechanism of actualization, and extended for all the years of the economic life estimated for the investment. It is calculated using the following equation:

$$NPV = \sum_{t=0}^n \frac{Cash\ flow}{(1+i)^t}$$

When as i varies, the NPV is equal to zero, the correct value of the Internal Rate of Return will have been found. This will be the fundamental parameter that an investor company will assess in order to decide if a given project is economically advantageous.

The value obtained with an interest rate of 5 % is 6.015.292,97 €.

- **IRR** (Internal Rate of Return): indicates the rate of return of a given investment. In general, under a certain value of IRR a company considers it impractical to invest in a given product and that is why this value is fundamental in economic analysis. The internal rate of return is a discount rate that makes the net present value (NPV) of all cash flows equal to zero. IRR calculations rely on the same formula as NPV does. The discount rate means the interest rate to be used to transfer at the time zero, a financial capital receivable at a certain future date, so that that discounted capital, that is receivable today, is financially equivalent to the capital receivable in the future date.

The value obtained is equal to 17,16 %.

- **PBT** (Pay Back Time): indicates the return time of the investment. The time when Cumulated Cash Flow becomes positive, the investment is repaid, and that is the time that determines the Pay Back Time.

The Pay Back Time and the Cumulative Cash Flow of the latter indicate the real gain that the investment can bring in the coffers of the company at the end of life.

By applying an interest rate of 5%, the discounted cash flow for each year and the cumulative cash flow were calculated, as shown in the Table 27.

Table 27 - Discounted Cash Flow

YEAR	DISCOUNTED CASH FLOW	CUMULATIVE DISCOUNTED CASH FLOW
2021	-7.085.000,00 €	-7.085.000,00 €
2022	1.374.963,50 €	-5.710.036,50 €
2023	1.285.758,63 €	-4.424.277,88 €
2024	1.207.071,92 €	-3.217.205,95 €
2025	1.133.994,33 €	-2.083.211,62 €
2026	1.061.594,96 €	-1.021.616,66 €
2027	993.984,15 €	-27.632,51 €
2028	931.251,08 €	903.618,57 €
2029	871.288,04 €	1.774.906,61 €
2030	813.925,93 €	2.588.832,54 €
2031	771.765,16 €	3.360.597,70 €
2032	730.334,35 €	4.090.932,05 €
2033	603.848,84 €	4.694.780,89 €
2034	570.761,82 €	5.265.542,71 €
2035	539.789,67 €	5.805.332,38 €
2036	510.725,25 €	6.316.057,62 €

From the graph 40, it can be seen that by applying the interest rate of 5% the cumulative cash flow will become positive starting from 2028, therefore one year more than in the previous graph.

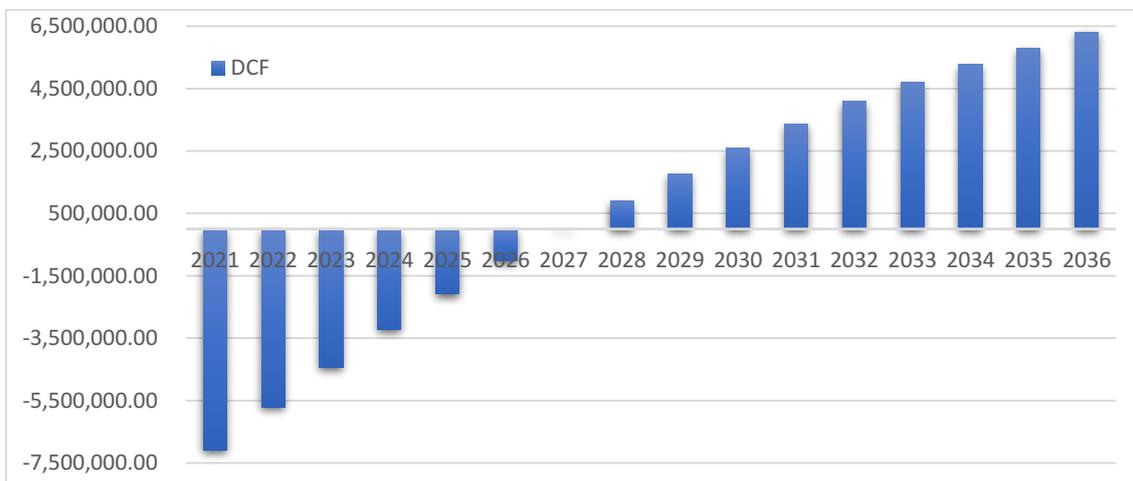


Figure 40 - Cumulative Cash Flow with an interest rate of 5% Scenario 1

This is the scenario that involves the purchase of electricity both from the existing photovoltaic plant in the area of interest, Ancona, and from the electricity grid to complete the energy demand of the electrolyser equal to 6250 MWh/year.

Now we analyse also the ideal case, with the same conditions and with the same inputs evaluating the case in which the existing plant was able to produce the energy needed to power the electrolyser.

The Table 28 summarized the new values obtained of OPEX and EBITDA.

Table 28 – Opex and EBITDA

YEAR	OPEX WATER SUPPLY	OPEX O&M	OPEX ENERGY COST PV	EBITDA
2021	0,00 €	0,00 €	0,00 €	-7.085.000,00 €
2022	10.800,00 €	275.500,00 €	372.442,54 €	2.041.257,46 €
2023	10.800,00 €	275.500,00 €	393.367,26 €	2.006.832,74 €
2024	10.800,00 €	275.500,00 €	406.529,82 €	1.980.237,68 €
2025	10.800,00 €	275.500,00 €	418.111,11 €	1.955.291,05 €
2026	10.800,00 €	275.500,00 €	435.711,44 €	1.924.392,21 €
2027	10.800,00 €	275.500,00 €	452.558,71 €	1.894.312,93 €
2028	10.800,00 €	275.500,00 €	467.906,05 €	1.865.799,72 €
2029	10.800,00 €	275.500,00 €	485.167,25 €	1.835.438,49 €
2030	10.800,00 €	275.500,00 €	504.531,41 €	1.803.039,81 €
2031	10.800,00 €	275.500,00 €	498.854,32 €	1.795.747,54 €
2032	10.800,00 €	275.500,00 €	496.482,11 €	1.785.215,24 €
2033	10.800,00 €	275.500,00 €	494.109,90 €	1.774.747,47 €
2034	10.800,00 €	275.500,00 €	491.737,69 €	1.764.343,89 €
2035	10.800,00 €	275.500,00 €	489.365,48 €	1.754.004,19 €
2036	10.800,00 €	275.500,00 €	486.993,27 €	1.743.728,06 €

Applying as in the previous case, a depreciation rate of 9% and considering taxes to 24% the following values showed in the Table 29 were obtained.

Table 29 - Cash Flow

YEAR	NET CASH FLOW	CUMULATED CASH FLOW	DISCOUNTED CASH FLOW	CUMULATED DISCOUNTED CASH FLOW
2021	-7.085.000,00 €	-7.085.000,00 €	-7.085.000,00 €	-7.085.000,00 €
2022	1.704.391,67 €	-5.380.608,33 €	1.623.230,16 €	-5.461.769,84 €
2023	1.678.228,88 €	-3.702.379,44 €	1.522.203,07 €	-3.939.566,77 €
2024	1.658.016,64 €	-2.044.362,81 €	1.432.257,11 €	-2.507.309,66 €
2025	1.639.057,20 €	-405.305,61 €	1.348.456,41 €	-1.158.853,24 €
2026	1.615.574,08 €	1.210.268,47 €	1.265.844,56 €	106.991,32 €
2027	1.592.713,82 €	2.802.982,29 €	1.188.507,58 €	1.295.498,90 €
2028	1.571.043,79 €	4.374.026,08 €	1.116.511,49 €	2.412.010,39 €
2029	1.547.969,26 €	5.921.995,34 €	1.047.726,52 €	3.459.736,91 €
2030	1.523.346,26 €	7.445.341,59 €	981.962,58 €	4.441.699,49 €
2031	1.517.804,13 €	8.963.145,72 €	931.800,07 €	5.373.499,56 €
2032	1.509.799,58 €	10.472.945,30 €	882.748,55 €	6.256.248,11 €
2033	1.348.808,07 €	11.821.753,38 €	751.066,81 €	7.007.314,91 €
2034	1.340.901,36 €	13.162.654,74 €	711.108,62 €	7.718.423,53 €
2035	1.333.043,19 €	14.495.697,92 €	673.277,39 €	8.391.700,93 €
2036	1.325.233,32 €	15.820.931,25 €	637.459,89 €	9.029.160,81 €

Figures 41 and 42 show the trend of the cumulated cash flow and of the discounted cash flow with an interest rate of 5%. It can be seen that in the first graph, the value will return to positive starting from 2027, while in the second graph starting from 2028.

An investment is considered convenient if the value of the PBT is about 8/10 years over an overall plant life of 15 years and the IRR value is equal or higher than 8%. The Cumulated Cash Flow must be as high as possible.

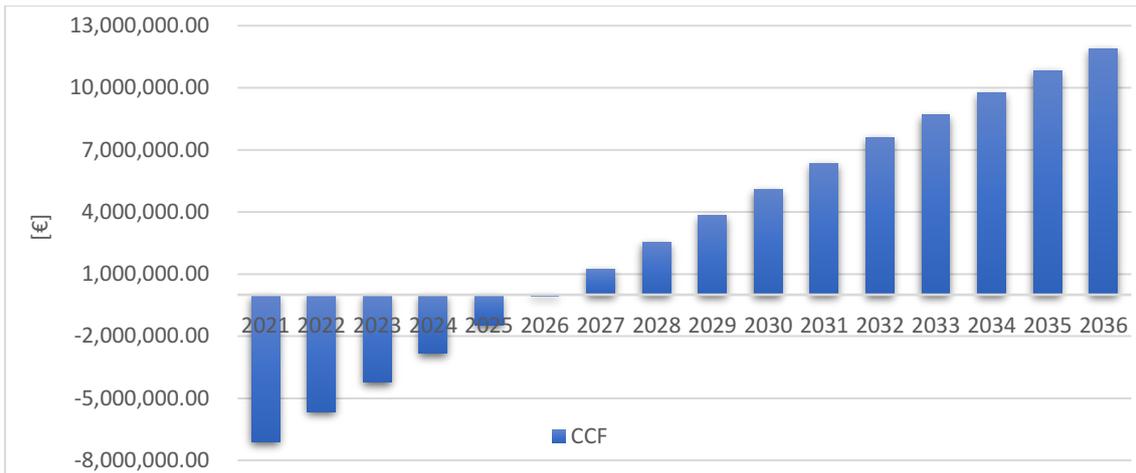


Figure 41 - Cumulated Cash Flow Ideal Scenario

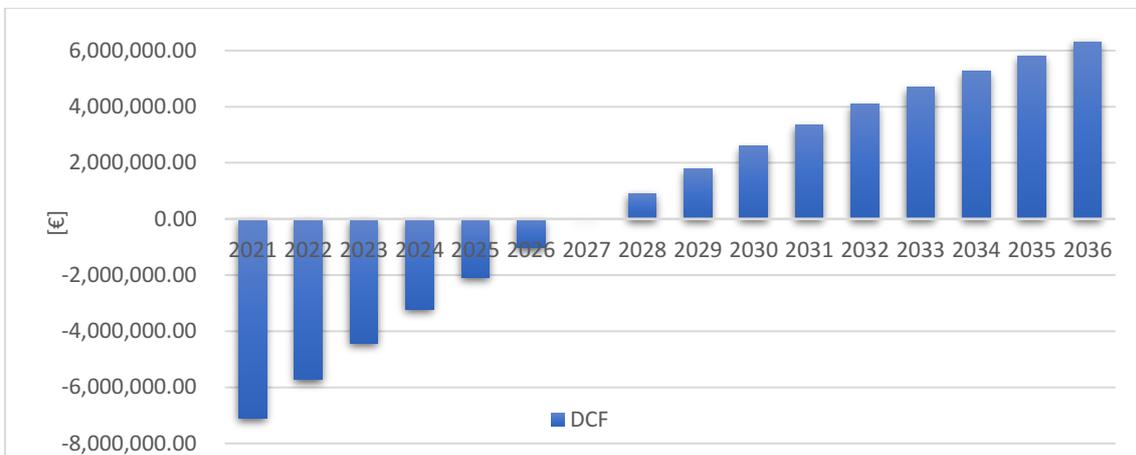


Figure 42 - Discounted Cash Flow Ideal Scenario

The graph shows a 7-year Pay Back Time as in the first case, this means that after 7 years the initial CAPEX has been covered and in the remaining time all the earnings go directly into the investor's coffers.

Compared to the first case, a higher IRR equal to 19,90% and an NPV of € 5.958.331,53 was obtained.

6.7 SCENARIO 2

In this scenario, it is assumed to realize the Hydrogen and Oxygen plant powered a new photovoltaic system.

Thanks to the use of the Photovoltaic Geographical Information System, it has been estimated the producibility of the tracking photovoltaic system, equal to 1832,76 kWh/kW per year, assuming to place it in the area of Ancona, as studied by the market analysis.

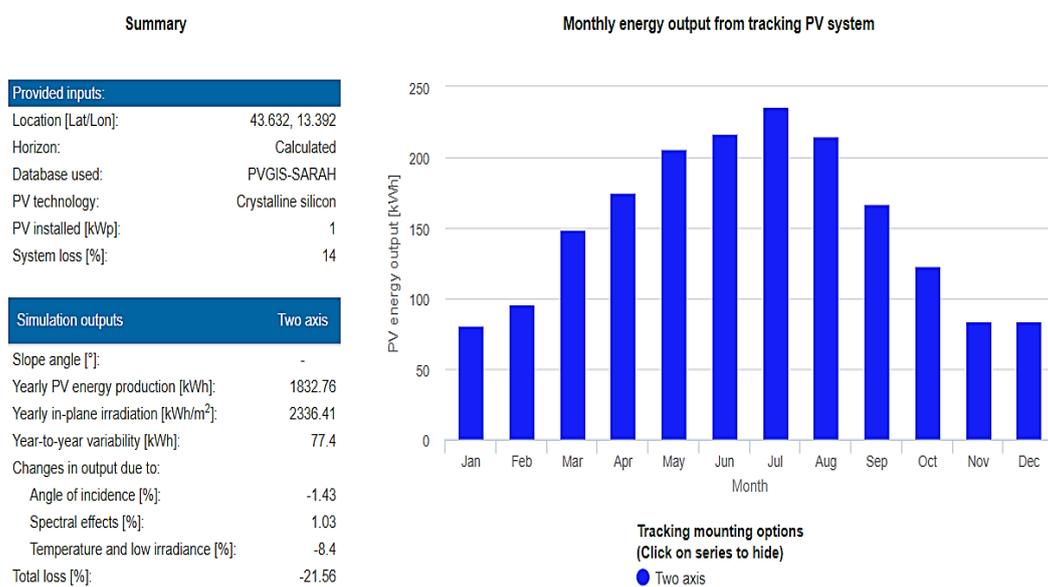


Figure 43 - Result of Photovoltaic Geographical Information System

Assuming to install a 5 MW photovoltaic system, the total producibility is 9163,8 MWh/year, using 6250 MWh to power the electrolyser. The rest of the energy produced will be sold.

In this case, the economic assessment will therefore take into account the costs of construction the photovoltaic system and not take into account the cost of energy to power the electrolyser.

6.7.1 CAPEX SCENARIO 2

In addition to the costs shown in the Scenario 1, the costs of the photovoltaic system will be added. Assuming to install a photovoltaic system with a power of 5 MW, the CAPEX will be equal to 3.000.000,00 €.

The final value of CAPEX, including the photovoltaic system and the Hydrogen-Oxygen system is summarized in the Table 30.

Table 30 – CAPEX Scenario 2

CAPEX ASSUMPTIONS	
PV system	3.000.000 €
H ₂ -O ₂ system	7.085.00 €
TOTAL CAPEX	10.085.000 €

6.7.2 OPEX SCENARIO 2

As for scenario 1, OPEX of photovoltaic system and H₂-O₂ system are considered. In this case the costs are:

- Cost relatively of photovoltaic system, including all operation and maintenance costs, equal to 75.000,00 € per year;
- Water supply, considering a water consumption of the electrolyser of 300 m³ per year and a water supply cost of 3,60 euros per m³;
- Operation and maintenance O&M of H₂-O₂ system, valued at 5% of the cost of the containers.

In the Table 31 all the costs are summarized to obtain the total OPEX for different years.

Table 31 -Total Opex Scenario 2

YEAR	OPEX PV	OPEX WATER SUPPLY	OPEX O&M	TOTAL OPEX
2021	0,00 €	0,00 €	0,00 €	0,00 €
2022	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2023	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2024	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2025	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2026	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2027	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2028	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2029	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2030	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2031	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2032	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2033	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2034	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2035	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €
2036	75.000,00 €	10.800,00 €	275.500,00 €	361.300,00 €

6.7.3 ECONOMIC RESULTS SCENARIO 2

As in Scenario 1, revenues from the sale of Hydrogen and Oxygen are calculated with sales prices of 1,50 €/Nm³ and 3,00 €/Nm³ respectively.

In this scenario, revenues from the sale of electricity is added to these revenues, with a sell price based on PUN (Prezzo Unico Nazionale).

In the Table 32 all the costs are summarized to obtain the total Revenues for different years.

Table 32 - Revenues

YEAR	REVENUES H ₂	REVENUS O ₂	REVENES PV	TOTAL REVENUES
2021	0,00 €	0,00 €	0,00 €	0,00 €
2022	1.350.000,00 €	1.350.000,00 €	144.497,69 €	2.844.497,69 €
2023	1.343.250,00 €	1.343.250,00 €	154.252,96 €	2.840.752,96 €
2024	1.336.533,75 €	1.336.533,75 €	160.389,45 €	2.833.456,95 €
2025	1.329.851,08 €	1.329.851,08 €	165.788,75 €	2.825.490,91 €
2026	1.323.201,83 €	1.323.201,83 €	173.994,16 €	2.820.397,81 €
2027	1.316.585,82 €	1.316.585,82 €	181.848,49 €	2.815.020,12 €
2028	1.310.002,89 €	1.310.002,89 €	189.003,54 €	2.809.009,32 €
2029	1.303.452,87 €	1.303.452,87 €	197.050,85 €	2.803.956,60 €
2030	1.296.935,61 €	1.296.935,61 €	206.078,58 €	2.799.949,80 €
2031	1.290.450,93 €	1.290.450,93 €	203.431,88 €	2.784.333,74 €
2032	1.283.998,68 €	1.283.998,68 €	202.325,93 €	2.770.323,28 €
2033	1.277.578,68 €	1.277.578,68 €	203.491,11 €	2.758.648,47 €
2034	1.271.190,79 €	1.271.190,79 €	202.546,19 €	2.744.927,77 €
2035	1.264.834,84 €	1.264.834,84 €	201.226,62 €	2.730.896,29 €
2036	1.258.510,66 €	1.258.510,66 €	199.614,99 €	2.716.636,31 €

With the same procedure applied for the Scenario 1, the values of EBITDA were calculated for the different years.

$$EBITDA = REVENUES - OPEX$$

In the Table 33 are summarized all the values obtained for the different years.

Table 33 - EBITDA

YEAR	EBITDA
2021	-10.085.000,00 €
2022	2.483.197,69 €
2023	2.479.452,96 €
2024	2.472.156,95 €
2025	2.464.190,91 €
2026	2.459.097,81 €
2027	2.453.720,12 €
2028	2.447.709,32 €
2029	2.442.656,60 €
2030	2.438.649,80 €
2031	2.423.033,74 €
2032	2.409.023,28 €
2033	2.397.348,47 €
2034	2.383.627,77 €
2035	2.369.596,29 €
2036	2.355.336,31 €

Applying as in the Scenario 1, a depreciation rate of 9%/year, the power plant will be deductible from the company's income for about 11 years with quotas of 907.650,00 € per year.

Considering taxes to 24%, the net cash flow, cumulated cash flow, discounted cash flow and cumulated discounted cash flow was calculated.

In the Table 34 are summarized all the correspondent values obtained for the different years.

Table 34 - Cash Flow

YEAR	NET CASH FLOW	CUMULATED CASH FLOW	DISCOUNTED CASH FLOW	CUMULATED DISCOUNTED CASH FLOW
2021	-10.085.000,00 €	-10.085.000,00 €	-10.085.000,00 €	-10.085.000,00 €
2022	2.105.066,24 €	-7.979.933,76 €	2.004.824,99 €	-8.080.175,01 €
2023	2.102.220,25 €	-5.877.713,50 €	1.906.775,74 €	-6.173.399,27 €
2024	2.096.675,29 €	-3.781.038,22 €	1.811.186,94 €	-4.362.212,32 €
2025	2.090.621,09 €	-1.690.417,13 €	1.719.959,14 €	-2.642.253,18 €
2026	2.086.750,34 €	396.333,21 €	1.635.023,49 €	-1.007.229,69 €
2027	2.082.663,29 €	2.478.996,50 €	1.554.115,42 €	546.885,73 €
2028	2.078.095,08 €	4.557.091,59 €	1.476.863,38 €	2.023.749,11 €
2029	2.074.255,02 €	6.631.346,60 €	1.403.937,44 €	3.427.686,55 €
2030	2.071.209,85 €	8.702.556,45 €	1.335.120,33 €	4.762.806,88 €
2031	2.059.341,64 €	10.761.898,09 €	1.264.257,13 €	6.027.064,01 €
2032	2.048.693,70 €	12.810.591,78 €	1.197.828,77 €	7.224.892,78 €
2033	1.821.984,84 €	14.632.576,62 €	1.014.549,33 €	8.239.442,12 €
2034	1.811.557,11 €	16.444.133,73 €	960.707,41 €	9.200.149,53 €
2035	1.800.893,18 €	18.245.026,91 €	909.573,43 €	10.109.722,96 €
2036	1.790.055,60 €	20.035.082,50 €	861.047,35 €	10.970.770,31 €

As for Scenario 1, Figures 44 and 45 show the trend of the cumulated cash flow and of the discounted cash flow with an interest rate of 5%. It can be seen that in the first graph, the value will return to positive starting from 2027, while in the second graph starting from 2028.

In the two scenarios, same Pay Back Time values were obtained, what will change will be the value of IRR.



Figure 44 - Cumulative Cash Flow Scenario 2

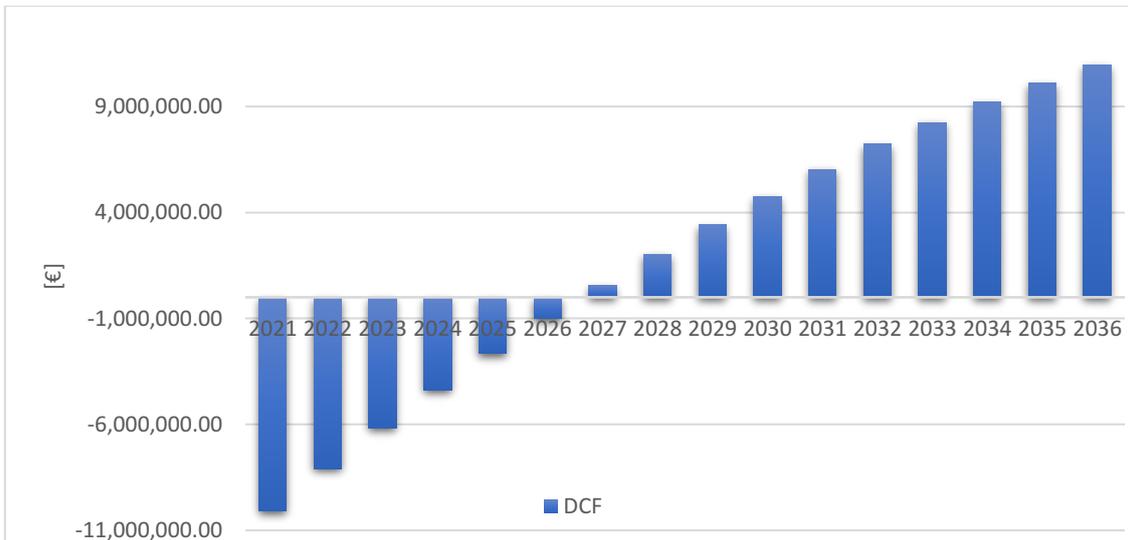


Figure 45 - Discounted Cash Flow Scenario 2

In Scenario 2, an IRR of 18,99 % and an NPV of € 10.448.352,67 was obtained. Compared to the ideal scenario, the IRR value is slightly lower in this case.

6.8 SCENARIO 3

In the last scenario, it was analysed H₂-O₂ system supplied directly by power from the grid.

6.8.1 CAPEX SCENARIO 3

As presented in Scenario 1, the CAPEX is given only by the initial investment of the H₂-O₂ plant. There are no other initial costs. In the Table 35 all the costs are summarized to obtain the total CAPEX.

Table 35 - CAPEX H₂-O₂ power plant

CAPEX ASSUMPTIONS	
Containers cost	5.450.000 €
Design, Authorization and other costs (15 % of containers cost)	817.500 €
Transportation, Civil and Electrical works (15 % of containers cost)	817.500 €
TOTAL CAPEX	7.085.000 €

6.8.2 OPEX SCENARIO 3

In this scenario, OPEX related of H₂-O₂ power plant and OPEX related to energy cost taken from the grid are considered.

- Water supply, considering a water consumption of the electrolyser of 300 m³ per year and a water supply cost of 3,60 euros per m³;
- Operation and maintenance O&M of H₂-O₂ system, valued at 5% of the cost of the containers;
- Cost of energy taken from the grid; the price of electricity is based on PUN (Prezzo Unico Nazionale). At this initial price, 150 €/MWh were added to obtain the final price of energy to power the electrolyser taking into account the costs of system charges, taxes, expenses for transport and management.

In the Table 36 are summarized all the values obtained for the different years.

Table 36 - OPEX Scenario 3

YEAR	OPEX WATER SUPPLY	OPEX O&M	OPEX ENERGY COST GRID	TOTAL OPEX
2021	0,00 €	0,00 €	0,00 €	0,00 €
2022	10.800,00 €	275.500,00 €	1.247.442,54 €	1.533.742,54 €
2023	10.800,00 €	275.500,00 €	1.268.367,26 €	1.554.667,26 €
2024	10.800,00 €	275.500,00 €	1.281.529,82 €	1.567.829,82 €
2025	10.800,00 €	275.500,00 €	1.293.111,11 €	1.579.411,11 €
2026	10.800,00 €	275.500,00 €	1.310.711,44 €	1.597.011,44 €
2027	10.800,00 €	275.500,00 €	1.327.558,71 €	1.613.858,71 €
2028	10.800,00 €	275.500,00 €	1.342.906,05 €	1.629.206,05 €
2029	10.800,00 €	275.500,00 €	1.360.167,25 €	1.646.467,25 €
2030	10.800,00 €	275.500,00 €	1.379.531,41 €	1.665.831,41 €
2031	10.800,00 €	275.500,00 €	1.373.854,32 €	1.660.154,32 €
2032	10.800,00 €	275.500,00 €	1.371.482,11 €	1.657.782,11 €
2033	10.800,00 €	275.500,00 €	1.373.981,37 €	1.660.281,37 €
2034	10.800,00 €	275.500,00 €	1.371.954,56 €	1.658.254,56 €
2035	10.800,00 €	275.500,00 €	1.369.124,11 €	1.655.424,11 €
2036	10.800,00 €	275.500,00 €	1.365.667,24 €	1.651.967,24 €

6.8.3 ECONOMIC RESULTS SCENARIO 3

As in Scenario 1, revenues from the sale of Hydrogen and Oxygen are calculated with sales prices of 1,50 €/Nm³ and 3,00 €/Nm³ respectively.

Table 37 - Revenues H₂- O₂

Revenues		
Revenues due to H ₂ production	1.350.000	€/year
Revenues due to O ₂ production	1.350.000	€/year

A degradation coefficient of 0,50 %/year has been estimated, in the Table 38 are summarized the revenues for the different years.

Table 38 – Total Revenues

YEAR	RENEUVES H ₂	REVENUES O ₂	TOT REVENUES
2021	0,00 €	0,00 €	0,00 €
2022	1.350.000,00 €	1.350.000,00 €	2.700.000,00 €
2023	1.343.250,00 €	1.343.250,00 €	2.686.500,00 €
2024	1.336.533,75 €	1.336.533,75 €	2.673.067,50 €
2025	1.329.851,08 €	1.329.851,08 €	2.659.702,16 €
2026	1.323.201,83 €	1.323.201,83 €	2.646.403,65 €
2027	1.316.585,82 €	1.316.585,82 €	2.633.171,63 €
2028	1.310.002,89 €	1.310.002,89 €	2.620.005,78 €
2029	1.303.452,87 €	1.303.452,87 €	2.606.905,75 €
2030	1.296.935,61 €	1.296.935,61 €	2.593.871,22 €
2031	1.290.450,93 €	1.290.450,93 €	2.580.901,86 €
2032	1.283.998,68 €	1.283.998,68 €	2.567.997,35 €
2033	1.277.578,68 €	1.277.578,68 €	2.555.157,37 €
2034	1.271.190,79 €	1.271.190,79 €	2.542.381,58 €
2035	1.264.834,84 €	1.264.834,84 €	2.529.669,67 €
2036	1.258.510,66 €	1.258.510,66 €	2.517.021,32 €

As for the previous cases, EBITDA, Net Cash flow, Cumulated Cash Flow, Discounted Cash Flow, Cumulated Cash flow are calculated; always taking into account a depreciation rate of 9%/year and taxed of 24%.

The value deductible from the company's income for about 11 years is equal to 637.650,00 € per year.

In the Table 39 all the costs are summarized.

Table 39 - Economic Results

YEAR	EBITDA €	NET CASH FLOW €	CUMULATED CASH FLOW €	DISCOUNTED CASH FLOW €	CUMULATED DISCOUNTED CASH FLOW €
2021	-7.085.000,00	-7.085.000,00	-7.085.000,00	-7.085.000,00	-7.085.000,00
2022	1.166.257,46	1.039.391,67	-6.045.608,33	989.896,83	-6.095.103,17
2023	1.131.832,74	1.013.228,88	-5.032.379,44	919.028,47	-5.176.074,70
2024	1.105.237,68	993.016,64	-4.039.362,81	857.805,11	-4.318.269,60
2025	1.080.291,05	974.057,20	-3.065.305,61	801.359,27	-3.516.910,33
2026	1.049.392,21	950.574,08	-2.114.731,53	744.799,66	-2.772.110,67
2027	1.019.312,93	927.713,82	-1.187.017,71	692.274,34	-2.079.836,33
2028	990.799,72	906.043,79	-280.973,92	643.908,41	-1.435.927,92
2029	960.438,49	882.969,26	601.995,34	597.628,35	-838.299,57
2030	928.039,81	858.346,26	1.460.341,59	553.297,65	-285.001,92
2031	920.747,54	852.804,13	2.313.145,72	523.547,76	238.545,83
2032	910.215,24	844.799,58	3.157.945,30	493.936,82	732.482,65
2033	894.876,00	680.105,76	3.838.051,06	378.708,33	1.111.190,99
2034	884.127,02	671.936,53	4.509.987,60	356.342,29	1.467.533,28
2035	874.245,56	664.426,62	5.174.414,22	335.580,59	1.803.113,87
2036	865.054,09	657.441,10	5.831.855,32	316.240,41	2.119.354,28

In Scenario 3, an IRR of 9,55 % and an NPV of € 2.018.432,65 was obtained.

Compared to other cases, the IRR value in this scenario is the lowest obtained.

The results in this scenario are not very promising, in fact from the graphs in the Figure 46 and 47, the Pay Back time has moved forward compared to the other scenarios.

This means that the time to recover the investment will be greater in this case.

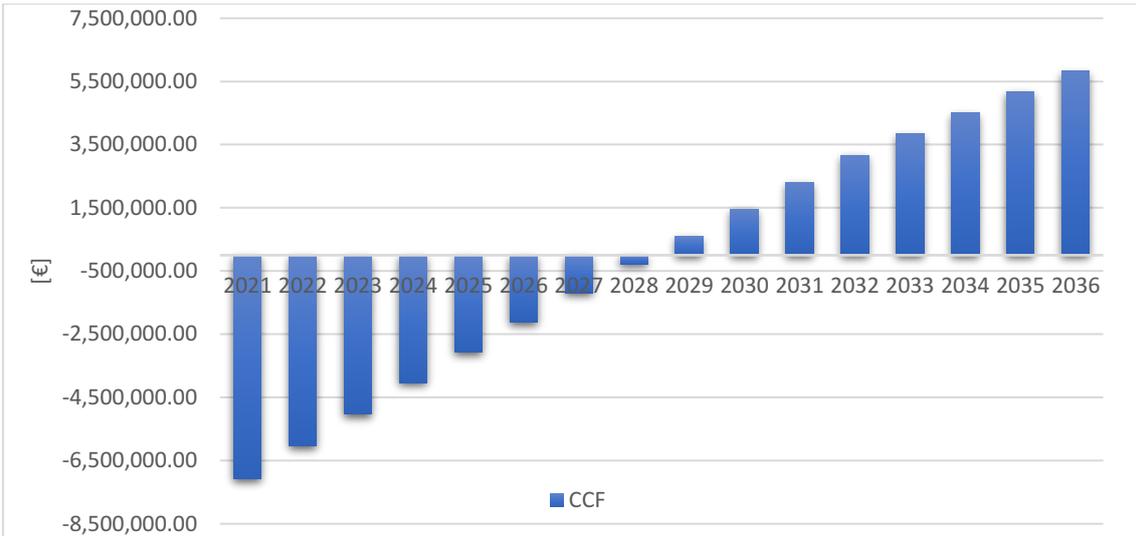


Figure 46 - Cumulated Cash Flow Scenario 3

It can be seen that from the year 2031 the value will turn positive, while for the other cases it will turn positive in 2027.

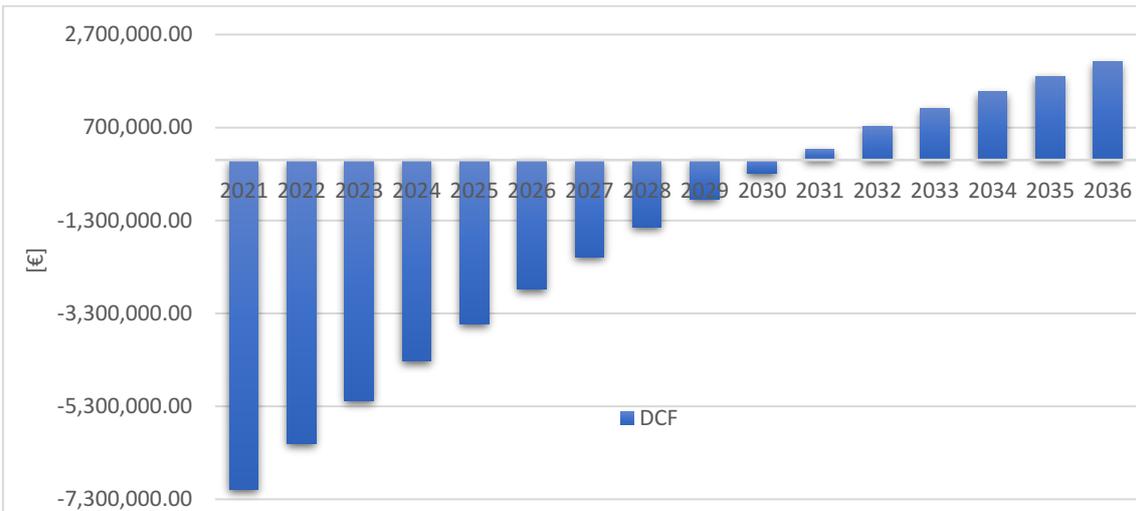


Figure 47 - Discounted Cumulated Cash Flow Scenario 3

6.9 ECONOMIC COMPARISON OF THE PRESENTED SCENARIOS

As described above, known as the major initial investment, it is possible to think of several scenarios applicable to that plant.

Summing up the discussion, the first assumed was the H₂-O₂ system powered by an existing photovoltaic system, owned by another user, then in the second scenario the hypothesis was analysed to power the plant with a photovoltaic plant owned and finally in the last scenario was analysed the plant powered by energy taken from the grid.

In the first scenario, since the existing photovoltaic system had a lower producibility than that required by electrolyser, part of the energy has also had to be purchased from the grid; in this regard it was also analysed an ideal case in which the plant had a higher production in order to completely feed the electrolyser.

Among the three different scenarios, analysing the IRR index which is the indicator that allows us to understand whether it is a good investment or not, the most profitable scenario is Scenario 2 with an IRR of 18,99 %.

In reality, the ideal case has a slightly higher IRR value of 19,90 % but this case has been studied more to show a comparison between a system powered entirely by solar energy and a system powered by both solar energy and electricity.

Scenario 3 is the most inconvenient of those analysed.

For the sake of clarity, the most influential parameter in the economic analyses is the sale price of the produced gases, supposed quite high in our elaboration. In the next years the challenge will be to find the right compromise, also by national and European incentives, between a high price that can satisfy the producer and a lower value, appreciated by the final user.

A final consideration to do is that analysing these scenarios shows that producing totally *green hydrogen* is the best choice, both in terms of investment and in terms of environmental sustainability.

CONCLUSION

The aim of this dissertation is to show one of the most valid alternatives to replacing traditional methods of energy production: *hydrogen*.

The gradual but continuous reduction of fossil fuel reserves and the environmental pollution problems that the use of these fuels determine, pose the need for a transition towards less polluting sources or energy carriers.

Hydrogen is not a form of primary energy, but requires a primary energy source in order to be produced and made available in the way and needs of the user.

It was highlighted in the second chapter how the particular characteristics of hydrogen make this gas the protagonist of a real revolution in the energy field.

The limitations on its diffusion that will be overcome are the costs of plants that affect the cost of energy produced making it still too high when compared with other fossil fuels, but it has also been shown that in the coming years the costs may decrease as a result of an expansion in the market of this gas and the continuous reduction in the cost of renewable resources.

Hydrogen can be produced by different methods from non-renewable sources and renewable sources; some of these do not produce CO₂ such as water electrolysis, while other techniques, such as SMR, coal gasification and partial hydrocarbon oxidation, being based on the use of fossil fuels, still have a significant environmental impact.

The most interesting prospect related to hydrogen is to produce it in a *green way* directly from solar energy, that is an inexhaustible and clean source.

With electrolysis can be produced both green hydrogen and oxygen, a key point of this dissertation.

Three different scenarios were analysed and compared to produce hydrogen and oxygen powered by photovoltaic energy or directly from energy taken from the grid. For each of these scenarios, an economic analysis was carried out, highlighting that investing in *green hydrogen is the best choice*.

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